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LATE QUATERNARY CLIMATE CHANGE AND HUMAN ADAPTATION IN ARID CHINA

D.B. MADSEN, F.H. CHEN AND X. GAO

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Illustration on front cover: shows “Looking across a Neolithic forager camp at an incoming dust storm, Jilantai basin, northeastern margin of the Tengger Desert, China” by D. Madsen

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LATE QUATERNARY CLIMATE CHANGE AND HUMAN ADAPTATION IN ARID CHINA

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Part I

INTRODUCTION

1

Archeology at the margins: Exploring the Late Paleolithic to Neolithic transition in China's arid west

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Abstract

The Holocene response to the dramatic climate change events in arid China during the Pleistocene/Holocene transition has not, until recently, been the subject of intensive study. This has been due to a continuing and long-standing split in Chinese archeology between the geo-chronological oriented study of the Paleolithic and the historiographic orientation of the Neolithic. This dichotomy has been reduced in the last few decades as Chinese and Western scholars have increasingly focused on the critical transition from the foragers of the Paleolithic to the farmers and pastoralists of the Neolithic. The chapters in this volume report the results of much of that recent work.

1. Introduction

The chapters in this volume revolve, for the most part, around the interplay between climatic and cultural change among the prehistoric foragers, early horticulturalists and initial pastoralists of China's arid west. Chronologically they focus on the transitional period between the Paleolithic foragers of the Late Pleistocene and the Neolithic farmers and pastoralists of the Early-to-Middle Holocene. For reasons we discuss below, this period has, until recently, been poorly studied despite it being critical to understanding one of the world's few areas where domesticated crops were independently invented (Smith, 1998). This situation is changing rapidly, and here we present a series of chapters that together provide a snapshot of current research on the human response to the Pleistocene/Holocene transition. While a number of similar collections are available for the Paleolithic period (e.g., Aigner, 1981; Wu and Olsen, 1985; Shen and Keates, 2003) and for the Later Neolithic and Bronze Age (e.g., Underhill, 1997; Liu, 2005), the lack of attention paid to the critical transitional period in these volumes is illustrative of a distinct gap in Chinese archeological research. Since a number of short histories on the development of archeology in China are available to English readers (e.g., Chang, 1981; Tong, 1995; Shi, 2001; Chang, 2002; Chen, 2003; Cao, 2005), we here explore only why and how that gap came to be, and how it is presently being reduced.

2. The Expedition Era

Archeology has deep roots in Chinese society in the form of material remains considered as part of cultural history. The collection and interpretation of bronze objects created by earlier dynasties was common during the Han Dynasty (from 206 BC to AD 220) and flowered during the later Song (AD 960–1279) and Qing (AD 1644–1911) dynasties, when ancient artifacts were primarily used as an aid in epigraphic studies (Shi, 2001; Cao, 2005). As a result, archeology in China, focused as it was on the study of inscriptions, started as an aspect of history, and it remained largely historical in focus even as it crystallized as an academic discipline during the twentieth century. Even as late as 1981 Chang noted "archeology remains a tool ... of Chinese historiography" (Chang, 1981: 156).

Formal archeological research in China began during the late nineteenth and early twentieth centuries following China's opening to the West. A number of foreign-led archeological expeditions, most notably those of Sven Hedin (e.g., Hedin, 1903) and Aurel Stein (e.g., Stein, 1903, 1912) produced dramatic interest in Chinese antiquities both worldwide and among the Chinese intellectual community. This antiquarian interest was not unlike that which laid the foundation for the growth of archeology as a discipline elsewhere, but differed from the growth of western archeology due to the extended Chinese historical record and the recovery of written records from archeological excavations beginning in 1899. The discovery of Buddhist writings in the Dunhuang Caves of western Gansu and the inscribed wooden tablets from the "lost city" of Lou-lan in the Taklimakan Desert of Xinjiang, for example, not only further stimulated an already focused epigraphic orientation in Chinese archeological studies, but also fostered a view of archeology as a nationalistic endeavor in response to what was little more than looting by some foreign explorers (e.g., von Le Coq, 1926).

After World War I, this nationalistic interest in China's past, combined with renewed interest in Chinese prehistory by foreign scholars, led to a decade or more of what could be called the Expedition Phase of Chinese archeology. During the 1920s and early 1930s, extended multi-year expeditions such as those of the "Central Asiatic Expedition" of the

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American Museum of Natural History (Andrews, 1932) and the French "La Croisière Jaune" expedition (Le Fèvre, 1935). All of these expeditions included professional foreign archeologists, as well as Chinese scholars, who as part of their participation in these projects often received archeological training at foreign universities. Many of these scholars, such as Pei Wenzhong (W.C. Pei), educated in France, and Li Ji (Li Chi), educated in the United States, went on to become the leaders of China's first archeological institutions.

In addition to these extended foreign expeditions, a number of expatriate foreign scholars working at China's educational and governmental institutions also began to train their Chinese colleagues as archeologists. These included the Canadian Davidson Black at Peking Medical College, the Swede Johan Gunnar Andersson at the Chinese Geological Survey, and the French Jesuit scholars Pierre Teilhard de Chardin and Emile Licent. While none of these men were professional archeologists, they were trained paleontologists, anatomists, and geological stratigraphers and helped define the initial descriptive classification systems for the Chinese prehistoric sequence. Many of these expatriate scholars assisted in the excavations of Zhoukoudian (Chou-k'ou-tien) in one way or another, and several, particularly Teilhard, linked what was in reality a relatively small, mixed community of Chinese and international scholars by serving on a number of different expedition projects.

3. Archeological Bureaucracy

The long-term Zhoukoudian excavations, oriented as they were to the recovery of the hominid fossils and cultural remains of "Peking Man", also served to focus a segment of this research community on the fossils and associated artifacts of China's Early-to-Middle Paleolithic period. This focus was formalized by the creation of the Cenozoic Research Laboratory in the Geological Survey of China in 1929. After the Communist Revolution, this office was reorganized in 1949 as part of the Institute of Paleontology of the Chinese Academy of Sciences, and reorganized again in 1957 as the Institute of Vertebrate Paleontology and Paleoanthropology (IVPP; Gujizhuidongwu yu Gurenlei Yanjiusuo). Regardless of its formal organization, this research group, with what may be seen loosely as an "archeology as geology" theoretical orientation, has remained focused on the study of human evolution within China restricted to the Paleolithic period.

An "archeology as history" research group was also formalized in the 1920s with the creation of an archeological research office within the Institute of History and Philology (Lishi Yuyan Yanjiusuo) of the Chinese Research Academy. In addition, an archeological research office was established within Chinese Studies at Peking University at about the same time. In 1950, these two organizations were combined into the Institute of Archeology of the Chinese Academy of Sciences (Zhonggou Kexueyuan) and eventually separated out with other social sciences into the Chinese Academy of Social Sciences (Zhongguo Shehui Kexueyuan). As the original name implies, this organization has always been oriented towards historiography and epigraphy and has limited its research almost exclusively to the Late Holocene period. Three sections of the institute are divided chronologically into pre-2000 BC archeology (but really limited to that after 10–12,000 ^{14}C yr BP), the archeology of the Xia through Zhou dynasties (∼2000–221 BC), and the archeology of the Han and later dynasties (after 221 BC).

This basic split between Neolithic archeology oriented towards the descriptive classification systems of history and Paleolithic archeology oriented to equally descriptive geology based on chronology and stratigraphy is, as a result, deeply embedded in the organizational structure (xitong) of Chinese archeological research. This dichotomy has permeated Chinese archeological research for more than 80 years. Much of this continued split has been due to the centralized nature of governmental organization, and it was only in the last decades of the twentieth century that provincial level archeological institutes and museums began to conduct their own archeological investigations on more than a limited basis and without substantial centralized oversight.

Much of this local work was undertaken under the auspices of the National Cultural Relics Bureau (Guojia Wenwuju), initially created in 1950, and was usually conducted in response to construction-related discoveries of archeological sites. The Cultural Relics Bureau and its provincial level offices are primarily regulatory and funding agencies, and, for the most part, take their lead in research orientation from the IVPP and the Institute of Archeology. This regulatory and funding structure thus served to reinforce the dichotomy between Paleolithic and Neolithic archeology.

4. Isolation and Politics

This split was further exacerbated by the cultural isolation of China through the middle years of the twentieth century and by a series of intense social upheavals such as the Great Proletarian Cultural Revolution of 1966–1976. Of equal import were the political pressures under which archeological research was conducted during the early decades of the People's Republic of China. Since the evolution of class society is such an integral part of Marxist theory, explanations for the development of Chinese civilization during the Neolithic were closely monitored (Von Falkenhausen, 1993; Tong, 1995), and the Institute of Archeology became highly politicized. The Paleolithic, on the other hand, particularly as related to hominid evolution and the Early-to-Middle Paleolithic, was deemed to be less critical to Marxist political thought, and, thus, less subject to political oversight (although only relatively; political pressure is certainly evident in some of the work of the IVPP during the middle years of the twentieth century). As a result, research conducted by the IVPP and associated universities and museums, tended to shy away from investigations of Late Paleolithic foragers and the antecedents to agriculture that might attract political pressure. Conversely, the Institute of

Archeology and its associated research groups tended to focus on the increasing complexities of agricultural societies, with little attention being paid their antecedents.

In short, until China began to open its doors to international research cooperation in the 1980s and increasingly in the 1990s, archeological research concerning the Pleistocene/Holocene transition and the development of incipient agriculture was something of an orphan. From the start of formal archeological research in the 1920s, there has been a split between the historiographic archeology of the Neolithic and the geochronologically based archeology of the Paleolithic. Furthermore, until the last few decades, this split was reinforced by political pressure that virtually precluded study of the transitional period.

The theoretical understanding of the processes through which this transition occurred has also been hampered by the dichotomy in research interests, by political pressures, and, particularly, by the relative isolation of Chinese archeological research. Much of this intellectual isolation was due to the massive social disruptions of the twentieth century. The Great Depression of the 1930s and the initiation of the Sino-Japanese War, World War II, the decades-long revolution culminating in the establishment of the People's Republic of China in 1949, the initial formation of governmental organizations and tight control of political thought in the 1950s, and the Cultural Revolution of the late 1960s and early 1970s, all served to isolate Chinese scholars from evolving archeological theory found in the rest of the world, including the former Soviet-Bloc. While a variety of theoretical and methodological advances changed the way archeology was conducted in the West, much of Chinese archeology remained limited to the typological classification schemes and descriptive orientation of the cultural historical approach developed in the 1920s and 1930s.

5. The New Wave

This limitation was openly recognized by the Chinese archeological community and, with the opening of China in the 1980s, Chinese archeological research began to change rapidly as Chinese archeologists began to interact more freely with their international counterparts and as international literature began to be more widely available in China. This increasing diversity in theoretical and methodological orientation accelerated in the 1990s and early years of the twenty-first century as the Chinese government began to actively encourage scholarly exchange and cooperation with international research groups. As a result, Chinese scholars educated abroad began to return in increasing numbers, bringing a wide array of new ideas and technological skills with them. This spirit of international cooperation and openness to different approaches laid the foundation for much of the work reported in this volume. In the last several decades, Chinese scholars interested in such topics as foraging theory, processes of animal domestication, the advent of pastoralism, and the initial manipulation of agricultural plants such as rice and millet, began to team with international scholars to investigate the great unknown void in Chinese prehistory. In China's arid west, the opening of many areas previously closed to foreign visitation in the last decades has also been critical to this increased research focus on the Pleistocene/Holocene transition.

Much of this new research has focused on the human response to environmental change and what could be called "environmental archeology" is now well established in Chinese archeological research. Most major projects in China are now multi-disciplinary in scope and a variety of environmental archeology programs have been developed in major Chinese universities. Because of the continued focus of archeological research on the Neolithic and the development of Chinese civilization, much of this more recent environmental archeology has been directed at identifying relationships between centennial- to millennial-scale climate change events during the Holocene (e.g., Chen *et al*., 2001; Jin and Liu, 2002; Huang *et al*., 2002; Wu and Liu, 2004; An *et al*., 2004; An *et al*., 2005). Increasing attention has also been paid to the impact of these relatively short climatic cycles on transitional foraging societies and the development of agriculture (Xia *et al*., 2002). Much of this research remains descriptive, however, and the mechanisms that might explain such linkages are not often explored.

6. Modeling the Paleolithic to Neolithic Transition

Much of the work that is reported in this volume represents an attempt to change that descriptive orientation. In the following chapters we explore the transition from the foraging societies of the Late Paleolithic to the emergence of settled farming societies and the initial pastoralism of the middle Neolithic. Because of significant differences with cultural evolution in the wetter monsoon areas of southeastern China, we focus on China's more arid west (Fig. 1) where millet agriculture and nomadic pastoralism were developed (for a brief review of the Paleolithic/Neolithic transition in southeastern China see Cohen, 2003; Wu and Zhao, 2003).

The environmental setting for this transition is provided by several chapters in the first section that together provide summaries of environmental change spanning Marine Isotope Stages 3–1 (~45,000 years ago to the present). These four chapters focus on changes in plant distributions and water availability, those aspects of the landscape that are most critical to human foraging societies. The first chapter by Wünneman *et al.* deals with Late Pleistocene and Holocene lake level fluctuations, respectively, and, by extension, changes in the amount and distribution of open water available to foragers in the region. The second, by Chen *et al*., combines multi-proxy data from a terminal desert lake with loess records from the Loess Plateau to explore centennial- to millennial-scale climate cycles and drought intervals on the margin of the East Asian monsoon during the post-glacial period. As the archeological chapters make clear, many of these events may have been critical in the evolution of both Upper Paleolithic and Neolithic

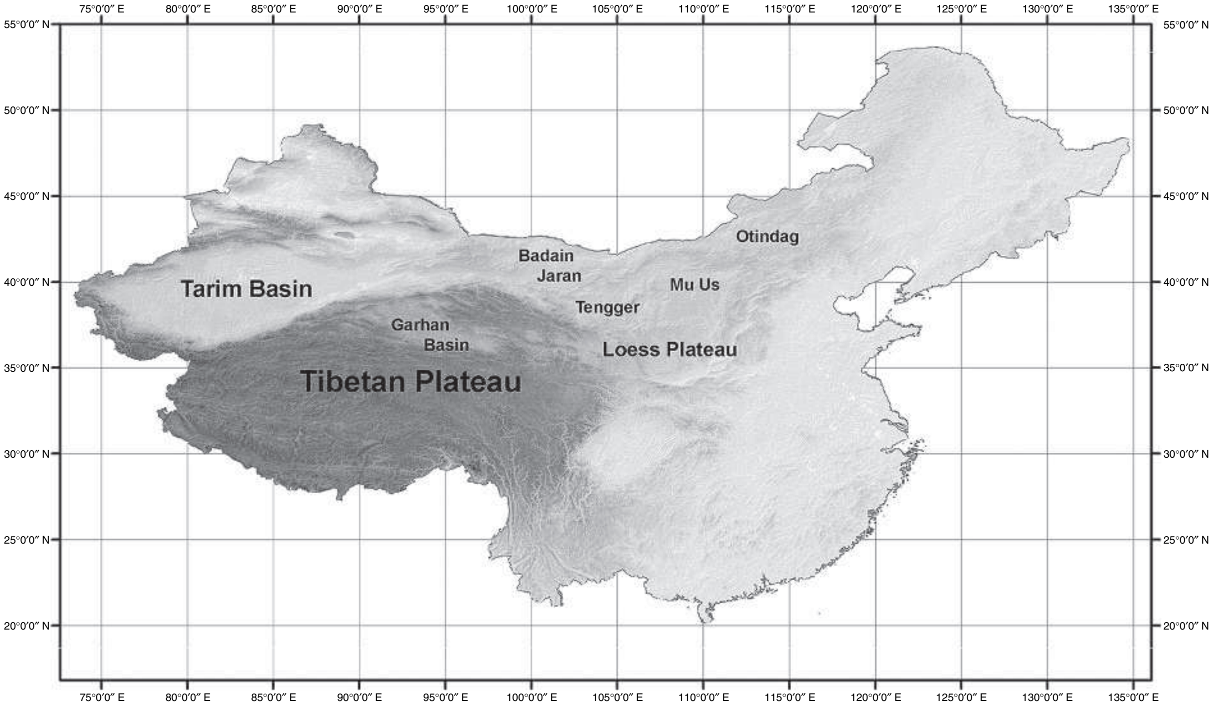

Fig. 1. Location of the Tibetan and Loess plateaus and the major desert regions of mainland China.

cultures. Chapters by Herzschuh *et al.* and Zhao *et al.* review pollen-based analyses of vegetation change, again during the Late Pleistocene and Holocene, respectively. Together these chapters also reflect the orientation of much recent paleoenvironmental research in China's arid west.

This is followed by a section with two theoretically oriented chapters by Madsen and Elston, and by Bettinger *et al.* that explore possible explanatory models for the links between climate and cultural change, particularly those that might have influenced the development of millet agriculture. Such theoretical issues remain poorly developed in Chinese archeological research and the chapters will hopefully contribute to ongoing discussions of these issues. They also provide a bridge between the chapters in the environmental section and the archeological chapters that follow in the third section.

These archeological chapters explore a variety of topics chronologically spanning the Late Pleistocene to Middle Holocene. The first chapter by Barton *et al.* examines the presence of foragers in northwestern China during the Last Glacial Maximum, a period previously thought to have limited occupation, and reviews the relationship between climate change and population expansions and contractions during Isotope Stage 2. Brantingham *et al.* follow by developing explanatory models for the occupation of the Tibetan Plateau during the Pleistocene/Holocene transition. This leads directly into the chapter by Aldenderfer that extends this discussion to the Tibetan Neolithic and reviews hypotheses on how the Neolithic in the dry uplands might have developed. Flad *et al.* also focus on the early Neolithic by reviewing animal domestication in China's northwest. Since much of the Mid-to-Neolithic in the region involved the development of pastoralism, this is a critical topic. Rhode *et al.* discuss one instance of domestication, that of the yak, and explore how the use of dung as fuel in highland environments may have been involved in that process.

Finally, in the concluding section, we try to summarize what these chapters tell us about the interaction between climate and culture in China's arid west during the Late Quaternary, and try to set the stage for future research. Clearly, these research questions are both diverse and numerous, but now that this critical transitional period is more open to archeological research they can begin to be addressed and answered.

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Part II

CLIMATE CHANGE

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2

Responses of Chinese desert lakes to climate instability during the past 45,000 years

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Abstract

Lake status records from desert lakes north of the Tibetan Plateau and in the vicinity of the Tien Shan display strong periodic alternations in lake hydrology and confirm synchronous and asynchronous reactions to monsoon climate variations and westerly wind driven dynamics over central Asia during the past 45,000 years. Centennial to millennial scale changes in lake status during the last glacial stage were in direct response to synchronous feedbacks of variations in the Asian monsoon and its reactions to large-scale ocean circulation and glacier dynamics in Greenland and Tibet. Since the onset of the Asian summer monsoon 13 ka ago, desert lakes have responded asynchronously with temporal and spatial shifts of some 100 years between short-term climate-induced variations in moisture availability.

1. Introduction

Although it is widely accepted that the main driving force of climate shifts in orbital bands is strongly related to solar radiation (insolation) through time (e.g. Berger and Loutre, 1991; Clement *et al.*, 2001; Leuschner and Sirocko, 2003), feedback mechanisms such as inland ice dynamics, thermohaline circulation and the atmospheric circulation pattern (e.g. the Northern Hemisphere low- and mid-latitude monsoon systems) may have affected land – ocean thermodynamic relations quite differently at regional scales. In particular, the climates over Asia seem to have been strongly influenced by the uplift of the Tibetan Plateau (TPL) (An *et al.*, 2001), co-controlling the evolution of the Asian monsoon system and the establishment of the Inner Asian dryland belt. However, palaeoclimate studies reveal the general high-frequency climate instability during the last glacial cycle, well known from Greenland ice cores and from North Atlantic sediment cores as stadials (Bond cycles, Heinrich events) and interstadials (Dansgaard – Oeschger cycles) on timescales of a few millennia (e.g. Dansgaard *et al.*, 1993; Bond *et al.*, 1997).

On the other hand, very little is known about feedback mechanisms controlling the expansion or shrinkage of arid regions in Inner Asia during the last glacial cycle and which of them might be dominant. The deserts north of the TPL and in the vicinity of the Tien Shan constitute large sedimentary areas with lake basins which appear to be long-term archives of water and sediment storage, indicating that a given lake status, reconstructed on the basis of various proxies, is in equilibrium with the prevailing climate. As most of these lake basins are connected with the glaciated high mountains, their water budgets and linked sedimentary processes are strongly influenced both by climate-controlled variations in the precipitation – evaporation pattern (P–E-ratio) and by tectonically induced changes in catchment topography and runoff characteristics. The special significance of this dryland belt in strongly continental China north of the TPL with respect to climate reconstructions is due to the fact that two different northern hemispheric air masses – the East Asian Monsoon and the extra-tropical westerlies intersect in this region. Both wind regimes are potential sources for water vapour transport, affecting the regional hydrological systems on the TPL and the desert forelands. Alternations in the summer monsoon strength as one prominent source for water vapour transport from low latitudes into the interior of China seem to have responded synchronously to major shifts in the climate system on a global scale, but on a regional scale the monsoonal effect varied considerably (An *et al.*, 2000).

Various lake records from north-western China north of the TPL confirm dramatic changes in water balance (Pachur *et al.*, 1995; Wünnemann *et al.*, 1998, Chen *et al.*, 2003; Zhang *et al.*, 2001, 2002, 2004) since the last glaciation, but until now it has remained uncertain which of the above-mentioned forcing mechanisms are responsible for changes in the hydrological conditions of each system. As all desert lakes in north-western China are far beyond or close to the modern limit of the Asian summer monsoon it would be of crucial interest to know whether lakes responded synchronously to climate variability in space and time and what have been the controlling factors for lake development at different places. Hence, we used lake records from the Chinese desert belt and transferred the data

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into lake status records as a base for a synoptic contribution towards a better understanding of climate influenced interrelations between the TPL and its forelands.

2. Methods and Data Base

Lake records used for status coding as documented in the Data Base Documentation of the Max Planck Institute for Biogeochemistry, Jena, Germany (Yu *et al.*, 2001) are based on the interpretation of multiple proxies derived from lake sediment structure and origin, geochemistry, biology and geomorphological features (palaeo-shorelines, etc.). Coding therefore represents a qualitative index of changes in lake level, area or relative water depth, thus documenting the water balance of each system.

Our study is based on lake status records of 15 sites of endoreic lake basins in China between 86–116° E and 37–46° N (Fig. 1), comprising five well-investigated lakes from Xinjiang Province (Manas lake, Bosten lake, Aiding lake, Lop Nor, Balikun lake), three palaeolakes from the western Alashan Plateau, Inner Mongolia, (western Gaxun Nur, Gaxun Nur main lake and Juyanze lake), four palaeolakes from the eastern Alashan Plateau, Gansu Province and Inner Mongolia (Hongshui river bank, Yiema lake, Duantouliang palaeolake, Tudungcao, Baijian lake) and two further lakes northeast of the Yellow River, Inner Mongolia (Yanhaize lake and Changannur), thus covering the Chinese dryland belt north of the TPL in an east-west transect. Our lake status records as demonstrated for selected lakes in Fig. 2 are based on available data from the literature also used in the Chinese Lake Status Data Base (Yu *et al.*, 2001) as well as on own investigations (e.g. Pachur *et al.*, 1995; Wünnemann *et al.*, 1998, 2007; Wünnemann, 2003; Hartmann, 2003; Chen *et al.*, 2003, 2005; Zhang *et al.*, 2002, 2004). They comprise five classes adapted to the collapsed coding system used in the Lake Status Data Base: 1 (extremely low or dry, hypersaline), 2 (low, saline or strong fluvial input), 3 (intermediate, slightly brackish), 4 (high, stable freshwater conditions, biologically active) and 5 (extremely high, freshwater conditions).

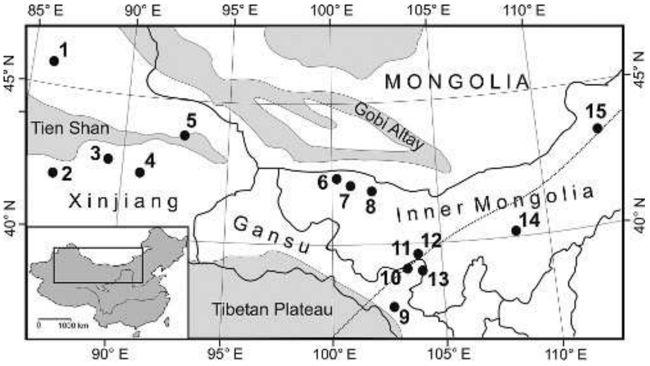


Fig. 1. Sketch map of north-western China with location of study sites. 1-Manas lake, 2-Bosten lake, 3-Aiding lake, 4-Lop Nur, 5-Balikun lake, 6-Gaxun Nur, west lake, 7-Gaxun Nur main lake, 8-Eastern Juyanze lake, 9-Hongshui (modern river bank), 10-Yiema lake (SJC), 11-Douantouliang, 12-Tudungcao, 13-Baijian lake, 14-Yanhaize lake, 15-Chagannur. The dashed line marks the modern boundary of the East Asian monsoon; the shaded areas mark the mountain regions in north-western China.

The chronology of each status is based on a total of 122 radiocarbon dates of lacustrine sediments, supplemented by 326 dates from the vicinities of the sites. Figure 3 shows the frequency of radiocarbon dates from sites north of the TPL versus time. The majority of dates derived from organic carbon refers to the Holocene period, while only few datasets from the Late Pleistocene are available so far. Despite possible errors of dates from lacustrine carbonates and shells, however, the histogram displays periods of low frequency or even lacking data. We assume that those time-windows may represent phases of unfavourable conditions in terms of lake formation.

All radiocarbon data were converted into calibrated ka BP using the standard calibration program (Stuiver *et al.*, 1998) as well as adapted equations to calculate ages on the base of the dataset of the Cariaco basin (Hughen *et al.*, 2004) for the time span older than 24,000 ^{14}C yr BP.

3. Results and Discussion

Except for two lakes (Fig. 1, nos 14 and 15) all the catchments are or were associated with glacier systems in the high mountains. Fig. 4A shows the record of mean lake status in 100-year intervals with a clear division into two parts: frequently high values from 45 to 25 ka and fluctuating but lower values from 25 ka to present time. In our opinion, the standard deviation (Fig. 4B) documents local hydrological peculiarities and climate impacts. Hence, individual lake evolution often conceals a global interplay between climatic events. In view of the shortage of available data for the period >25 ka, the chronology of the status codings remains tentative for this time span in comparison to the younger period. Nonetheless, our record is considered representative because averaging procedure was based on a sufficiently large number of lakes for each time interval (Fig. 4C).

3.1 Late Pleistocene Lake Status Records

During the interstadial episode of the last glaciation positive water budgets in the desert regions revealed large lakes (Pachur *et al.*, 1995) probably caused by both enhanced westwind and monsoon-driven moisture supply in the lake catchments. These processes seem to have run almost synchronously between Xinjiang in western China and the Yellow River as the approximate eastern limit of the study area. In our view, one main reason for the dominance of favourable hydrological conditions over more than 2000 km of longitude is the link between lake water budgets and glacier systems in the high mountains of the TPL and Tien Shan. We consider that the positive water budgets of the desert lakes between 44 and 25 ka (Fig. 5A) can only be explained by higher local precipitation in conjunction with very high melt water flow as the main controlling factors for lake status changes. This assumption fits in with ice-core data from Tibet (Thompson *et al*., 1997; Thompson, 2000), where fluctuations of the oxygen isotopes not only indicate temperature

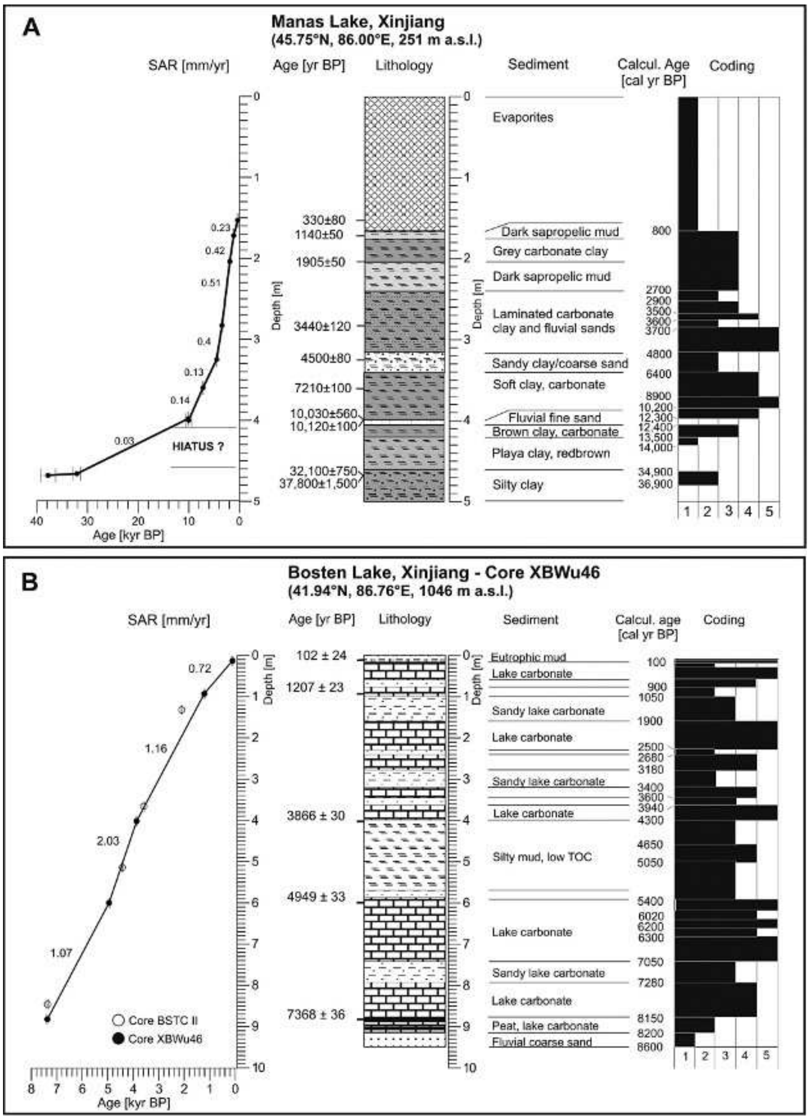
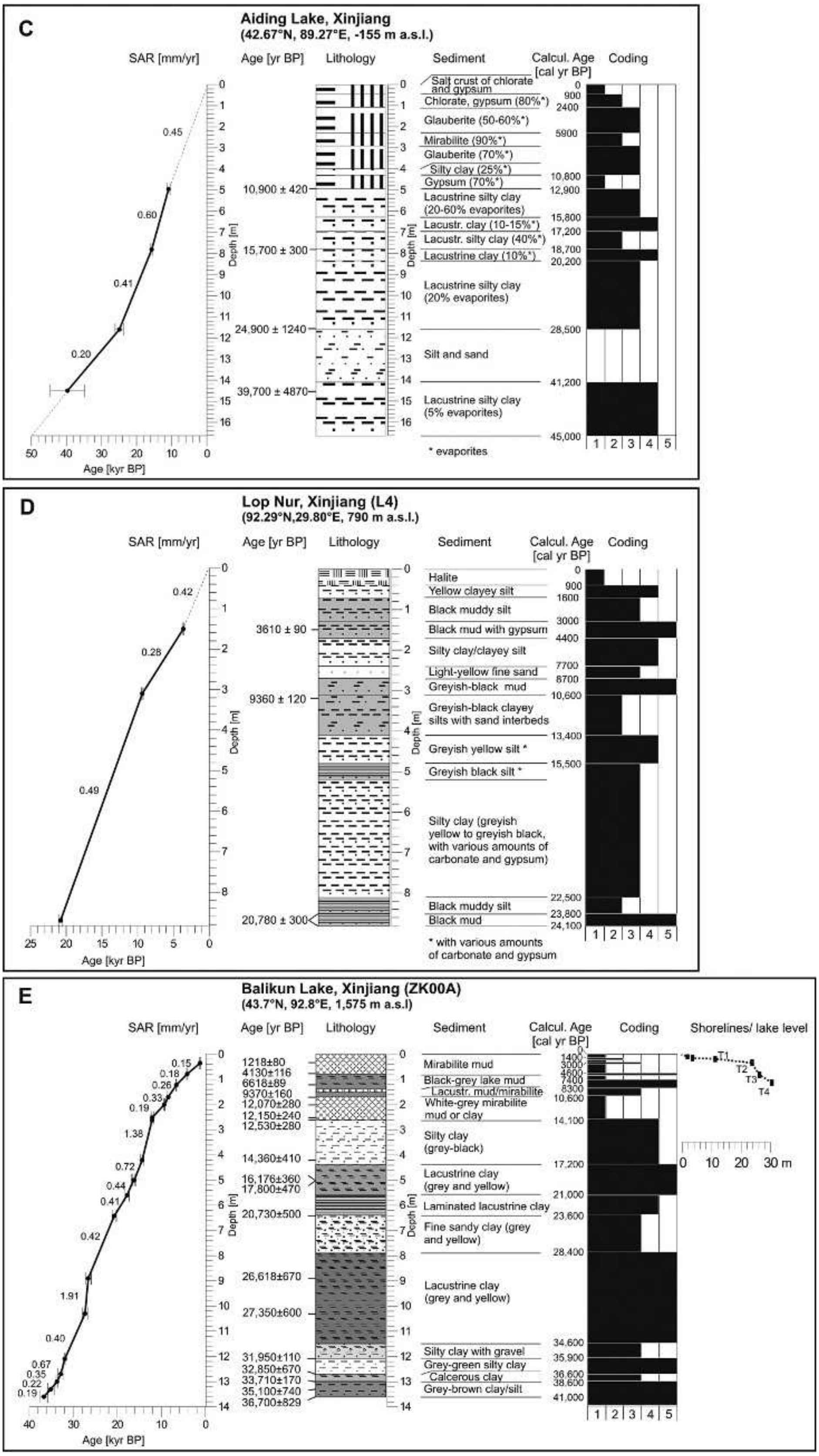


Fig. 2. Lake status records from arid China. Coding refers to results on lithology, geochemistry, fossil remains, morophology and radiocarbon dating. Age–depth relation with calculated sediment accumulation rates are the base for boundaries in lake status. A: Manas lake (Huang et al., 1987; Sun et al., 1994; Rhodes et al. 1996; Lin et al., 1996, Yu et al., 2001); B: Bosten lake (Wünnemann et al., 2003, 2007; Mischke and Wünnemann, 2006); C: Aiding Lake (Li et al., 1989; Yang et al., 1996, Yu et al., 2001); D: Lop Nur (Yu et al., 2001); E: Balikun lake (Yu et al., 2001); F: Gaxun Nur West (Wünnemann, 1999; Wünnemann and Hartmann, 2002; Wünnemannel et al., 2007). G: Gaxun Nur main basin (Wünnemann, 1999; Wünnemann and Hartmann 2002; Wünnemann et al., 2007); H: G36, Eastern Juyanze (Hartmann, 2003; Herzschuh et al., 2004). I: Hongshue river (Wünnemann, 1999; Zhang et al; 2000); J: Yiema Lake (SJC-section, Chen et al., 2003, 2005); K: Duatouliang section (Pachur et al., 1995; Wünnemann et al., 1998; Wünnemann, 1999; Zhang et al., 2001, 2002); L: Tudungcao section (Wünnemann et al., 1998); M: Baijian Lake (Pachur et al., 1995; Wünnemann et al., 1998; Wünnemann 1999; Zhang et al., 2002, 2004); N: Yanhaize Lake (Chen, C.T.A et al., 2003); O: Chagannur Lake (Yu et al., 2001).



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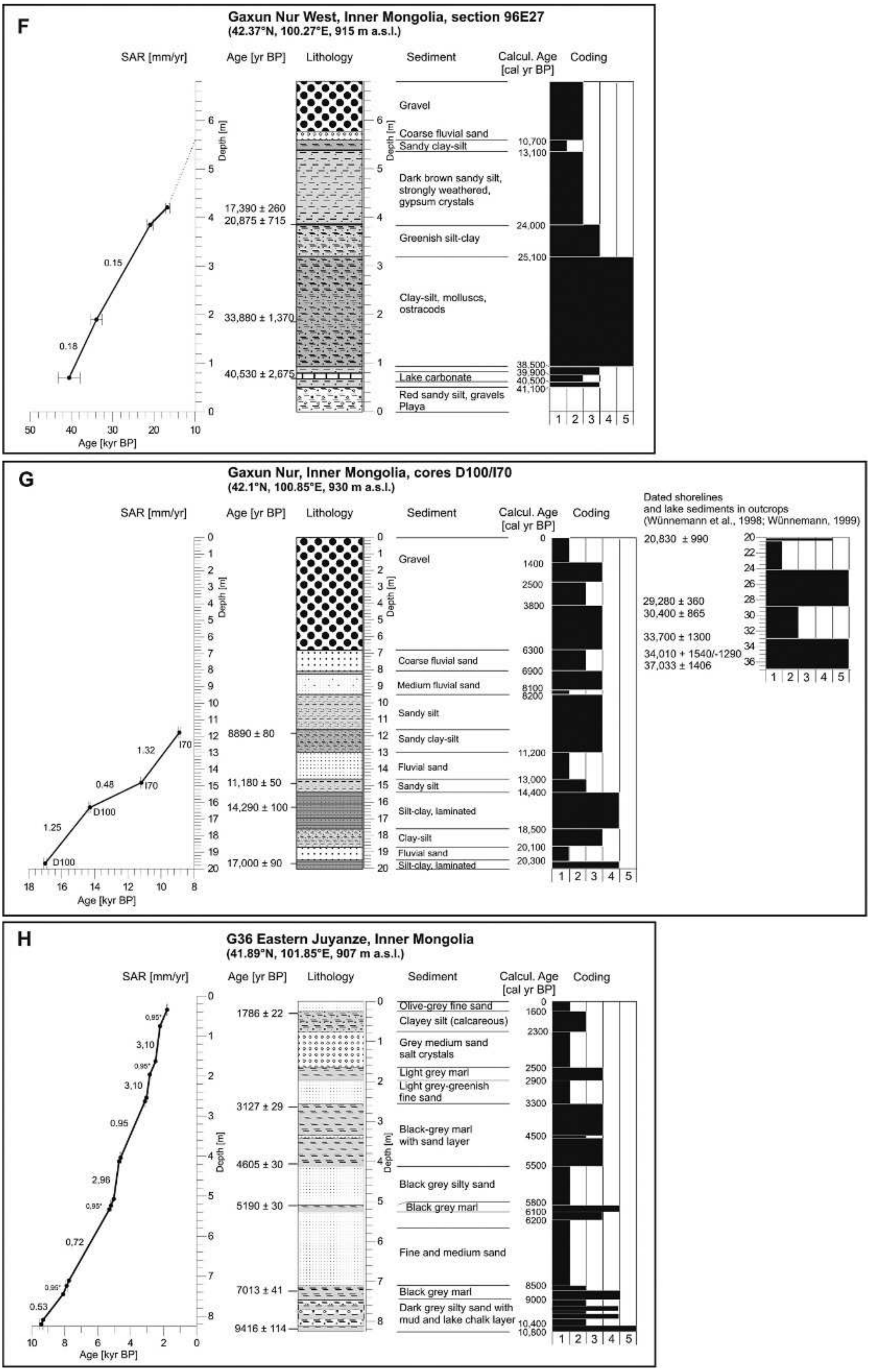

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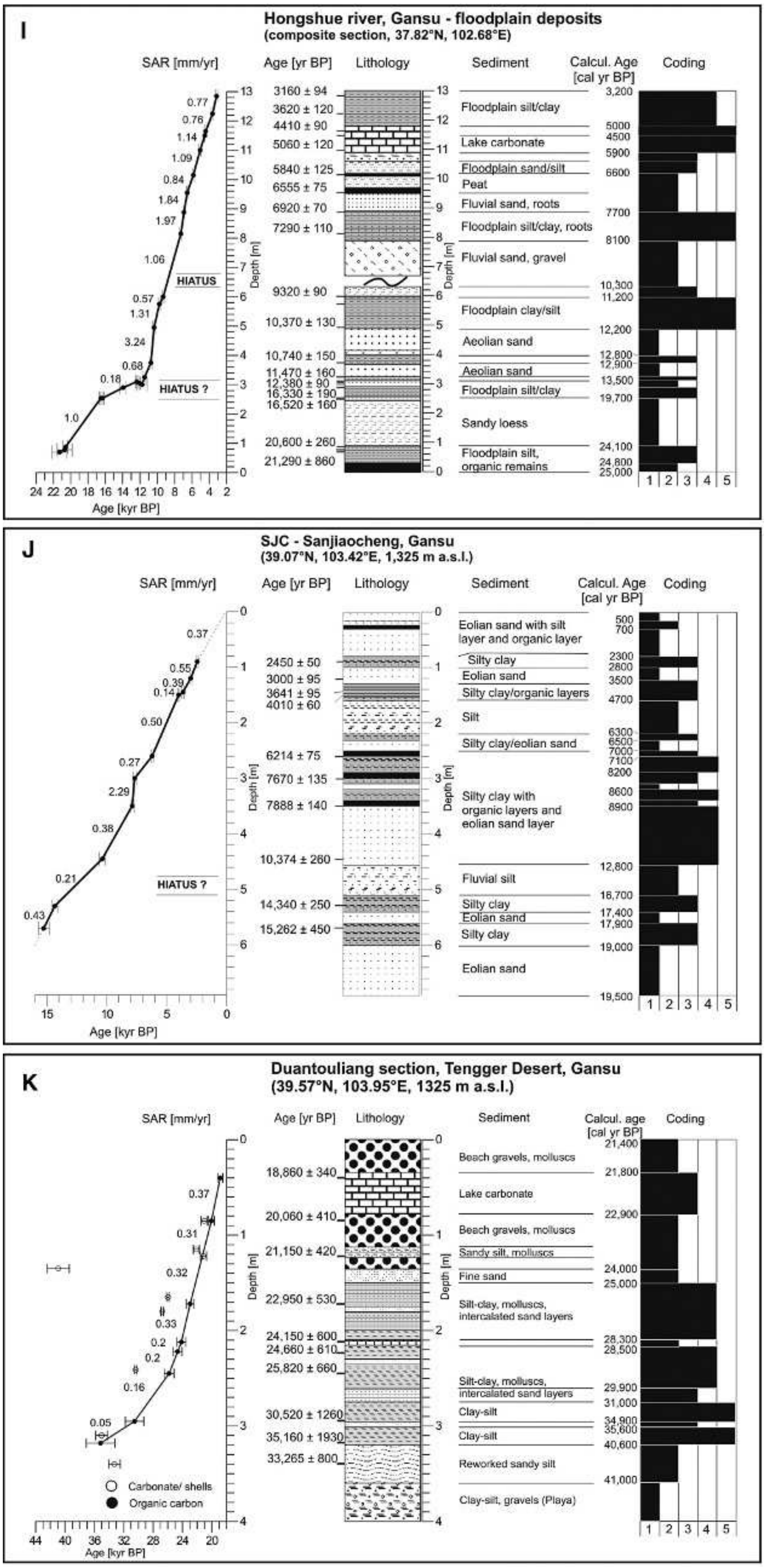

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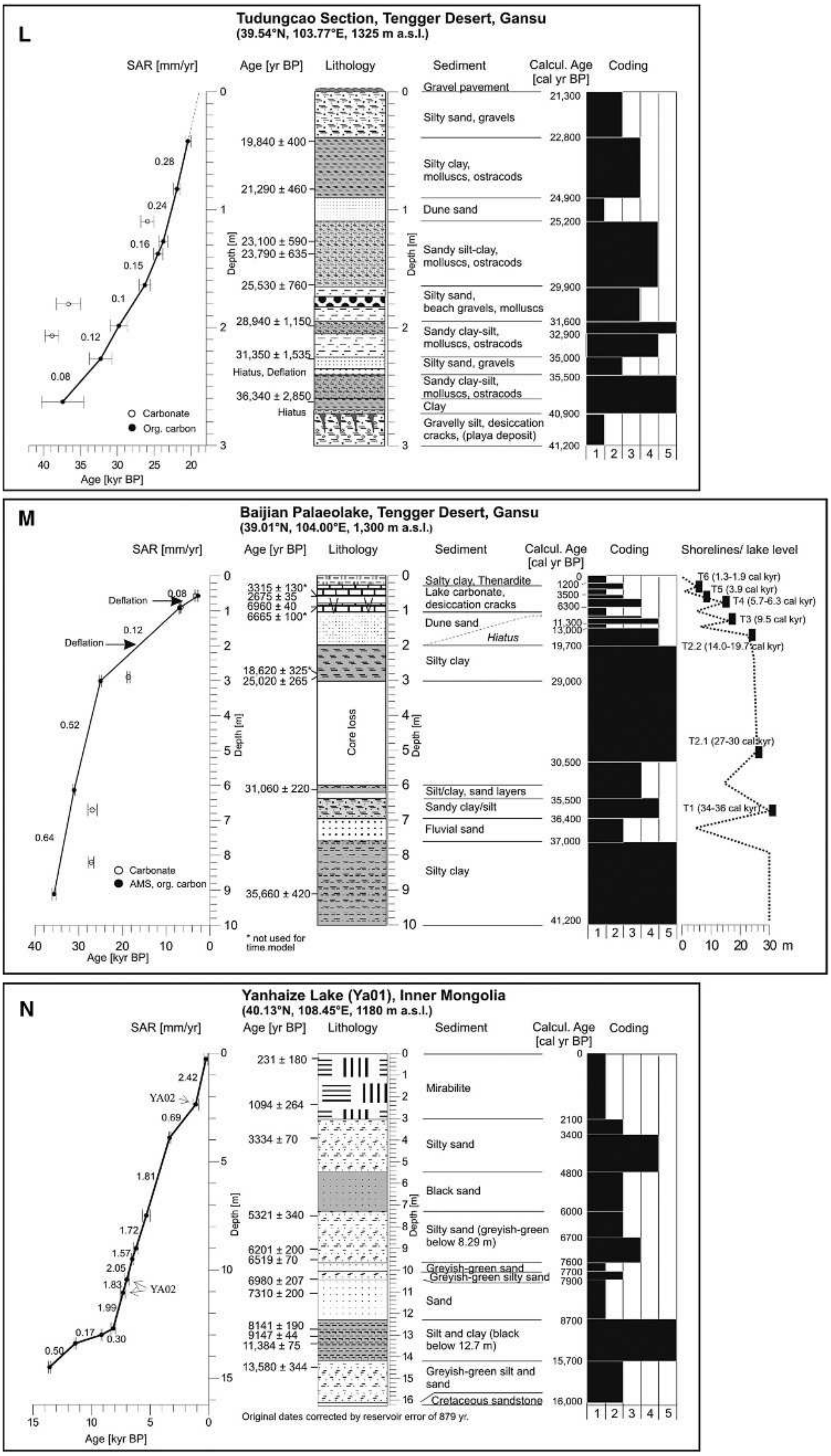

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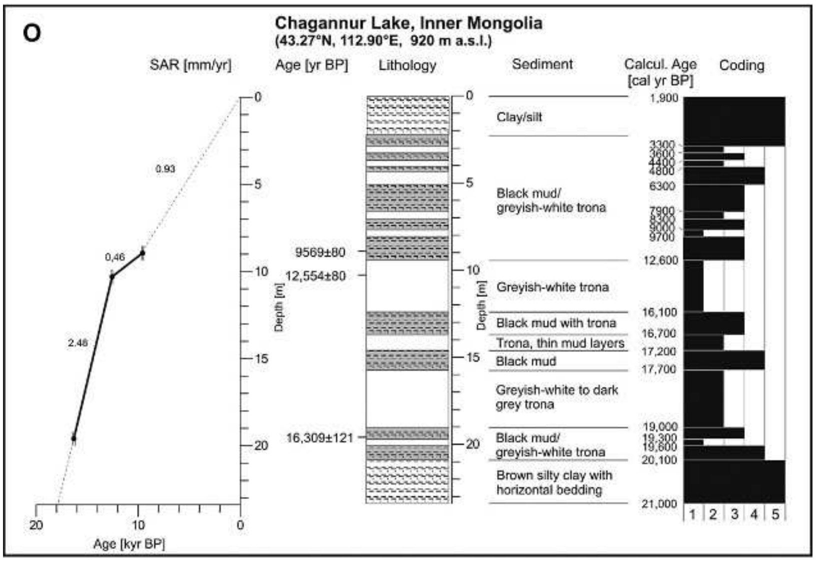

Fig. 2. (Continued)

changes in high-elevated regions of the TPL but also imply accumulation and decay of ice masses close to their margins. They largely correspond with water budget fluctuations of the foreland lakes (Fig. 5C). Although the stepwise depletion of $\delta^{18}O$ of the Guliya ice cap between 29 and 26 ka indicates lowering temperatures and probably expansion of Tibetan glaciers, melt water discharge to the northern forelands was still intensive enough to keep a high lake status, as we can judge from our data. Grain size studies from the Chinese Loess Plateau (Porter and An, 1995; Xiao *et al.*, 1995; An, 2000; Wünnemann *et al.*, 2006) suggest that at the same time dust flux (Fig. 5E) from north of the TPL was reduced as a result of a weak dry winter monsoon. However, a reverse trend towards a stronger influence of dry air masses north of the TPL is visible. This is supported by the fact that in south-eastern Chinese lowlands, the $\delta^{18}O$ in the Hulu Cave stalagmites (Fig. 5D) indicate a continuously reducing impact of tropical/subtropical precipitation derived from the monsoon.

Because of the low data resolution our record does not clearly exhibit the typical sawtooth pattern of the Dansgaard/Oeschger cycles that occurs periodically in the GISP2 record (Dansgaard *et al.*, 1993) (Fig. 5B). However, it is remarkable that periods of less water around 39/35.5, 31, 23.8 and 16 ka as well as glacier advance coupled with increased albedo at high elevations are apparently a teleconnected response to the thermohaline circulation system

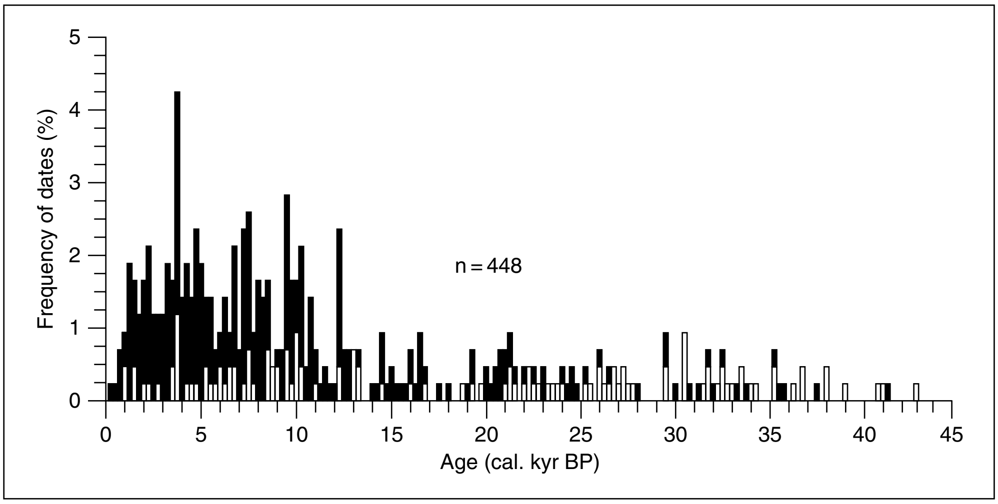

Fig. 3. Histogram of radiocarbon data from lake deposits north of the Tibetan Plateau. Black bars indicate the frequency of data from organic carbon. Light bars depict data from lacustrine carbonates and shells.

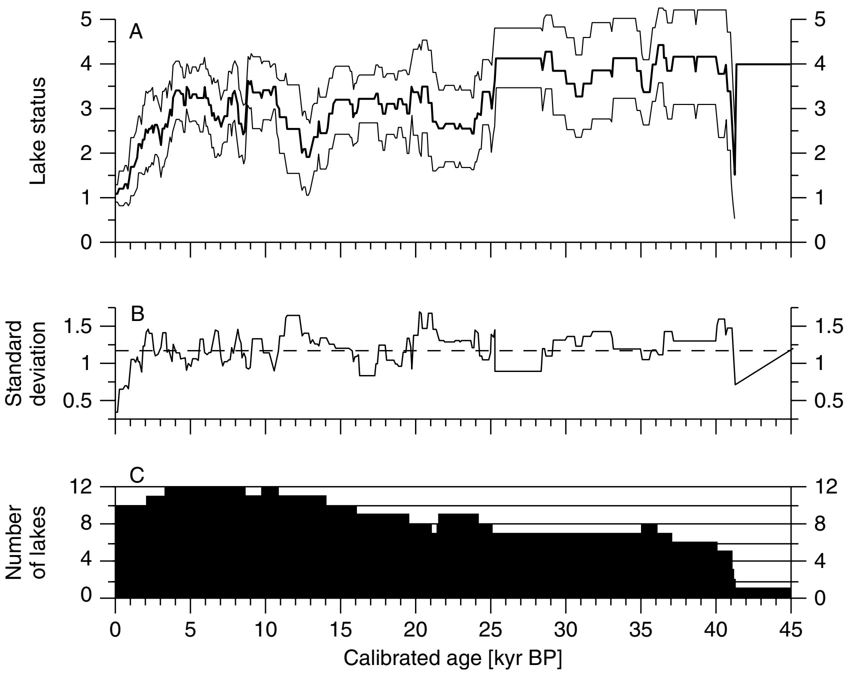

Fig. 4 Lake status record of central Asian desert lakes north of the Tibetan Plateau between 86–116° E and 37–46° N. A: Mean lake status record of the past 45 ka within 100-yr-intervals. Thin lines: upper and lower boundaries of 95%-confidence interval; B: Standard deviation of lake status, demonstrating the coherency and incoherency of the data for any given 100-yr-interval. The dashed line marks the mean deviation. C: Number of sites/lakes involved in lake status coding.

at that time and to massive freshwater discharges in the North Atlantic (Heinrich events 1–4; Bond *et al.*, 1997). Simultaneous decreases in sea surface salinity of the South China Sea (Wang *et al.*, 1998), increases of stalagmite oxygen isotopes (Wang *et al.* 2001; Yuan *et al.*, 2004) as well as changes in the lithogenic compounds and upwelling of the Arabian Sea (Leuschner and Sirocko, 2003) are further evidence of these interrelations. Hence, water budget changes of the desert lakes during the last glaciation are a direct response to glacier dynamics in Greenland and Tibet and thus to the variability of the monsoon system over China. However, a comparison of lake status records from Tien Shan and TPL (Qilian Shan, Fig. 6) discloses that in particular the TPL-connected lake catchments seem to show a more sensitive response to changes in moisture availability than the Tien Shan catchments, as far as we can judge from the limited data available. As changes in the radiation balance over Tibet caused a reduction of the summer pressure gradients between the TPL low and the Pacific high during the phase of gradual glacier growth (lower net insolation due to increased albedo and denser/longer cloudiness), thus pushing back the impact of the summer monsoon, we conclude that a substantial proportion of the rain/snow falling over Asia was also due to the shifting westwind system, as inferred for the Himalaya region at least (Benn and Owen, 1998). This is all the more true for the lakes in the Tien Shan catchment (Fig. 1, nos 1–5, Wünnemann *et al.*, 2005).

3.2 *Lake Status during the Last Glacial Maximum*

The Last Glacial Maximum (LGM) is clearly reflected in a striking negative water budget of the majority of desert lakes between 25 and 21 ka and matches the temperature-dependent negative $\delta^{18}O$ values of Greenland GISP2 ice core data (Fig. 5B). This minimum is also contemporaneous with Heinrich event H2 at 24 ka which seems to have occurred as a distinct event throughout China in lake deposits (Fig. 5A), ice cores (Fig. 5C), stalagmites (Fig. 5D) and loess sediments (Fig. 5E). It is also contemporaneous with the minimum of mid-June insolation at 40° N (Fig. 5F), corroborating model simulations (Kutzbach *et al.*, 1998; Kudrass *et al.*, 2001), which indicate a weakening of the summer monsoon during the LGM, also resulting in a reduced melt water discharge to the lacustrine basins. This dry period coincided with a much stronger winter monsoon, which was also responsible for an increased dust flux, (Fig. 5E), deposited as loess on the Chinese Loess Plateau (Porter and An, 1995; Xiao *et al.*, 1995; Wünnemann *et al.*, 2006). The existence of medium-to-low level lakes is not incompatible with phases of loess transport, taking into account that even a minor drop in lake level of large and shallow lakes would expose vast expanses of pelitic sediments for potential deflation (Wünnemann *et al.*, 2006). The synchronous response of all desert lakes implies that despite locally different catchment characteristics and wind regimes global climate deterioration affected lake hydrology everywhere in the study area.

With the weakening of the winter monsoon from 21 ka onwards the water budget returned to a medium-to-high level stability until about 15 ka (Fig. 5A). Compared with GISP2 and Guliya ice cores and loess data (Fig. 5A–C, E), the short-term fluctuations in lake hydrology between 21 and 15 ka, including the H1 event around 16 ka, broadly follow the climate-induced trends of glacier budgets in both Tibet and Greenland. However, lake status data from the whole of China revealed regional differences with drier conditions in eastern China as a result of reduced summer

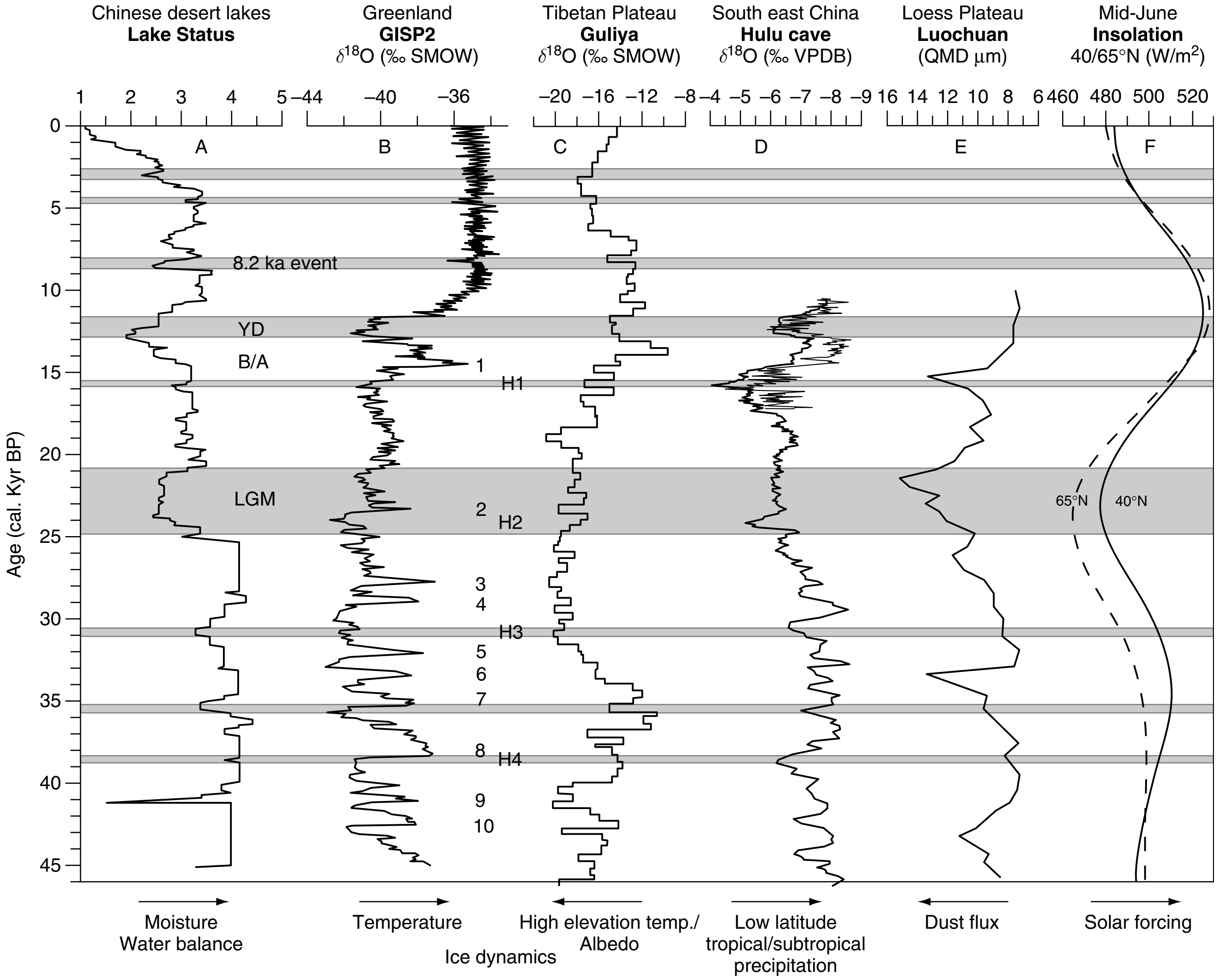

Fig. 5. Time series comparing lake status in north-western China with temperature-dependent (GISP2) and albedo related (Guliya) ice dynamics, tropical/subtropical precipitation pattern (Hulu Cave stalagmites), dust flux and insolation for the past 45 ka. The shaded areas mark important events; MIS: marine oxygen isotope stage. A: Lake status of desert lakes in north-western China. LGM: Last glacial maximum. YD: Younger dryas. B/A: Bølling/Allerød; B: GISP2 oxygen isotope record with Heinrich events (H1–H4) and Dansgaard/Oeschger cycles (1–10); C: Guliya oxygen isotope record; D: Stacked record from Hulu cave stalagmites, south-eastern China, including H82, YT (grey lines) and MSD/PD (black lines) records; E: Dust flux (grain size data from the Chinese Loess Plateau, Luochuan section. QMD: Quartz median diameter; F: Mid-JUNE insolation at 40° N (black line) and at 65° N (dashed line).

precipitation related to the established Pacific Subtropical High over eastern China (Yu *et al.*, 2003) at that period. The abrupt change in tropical and subtropical precipitation roughly between 18 and 15 ka as recorded in the Hulu and Dongge stalagmite records (Yuan *et al.*, 2004) support this deviation from climate conditions in north-western China. With respect to water balance it has to be considered that lakes in eastern China were not directly connected with glaciers and melt water discharge, thus resulting in lower status classes. This could also explain differences in lake status between eastern and western China.

3.3 Lake Status during the Last Termination

A second remarkable decline in lake status encompasses the last termination between 14.5 and 11.0 ka, starting during the Bølling warm interval and centring at the beginning of the GISP2-Younger Dryas cold-dry spell (Fig. 5). As the short-term oscillations of the Bølling – Allerød event had a minor impact on the water budget in China and could not reverse the negative trend, we conclude that melt water supply lost its influence on the water balance and was replaced in a stepwise fashion by the increase of summer

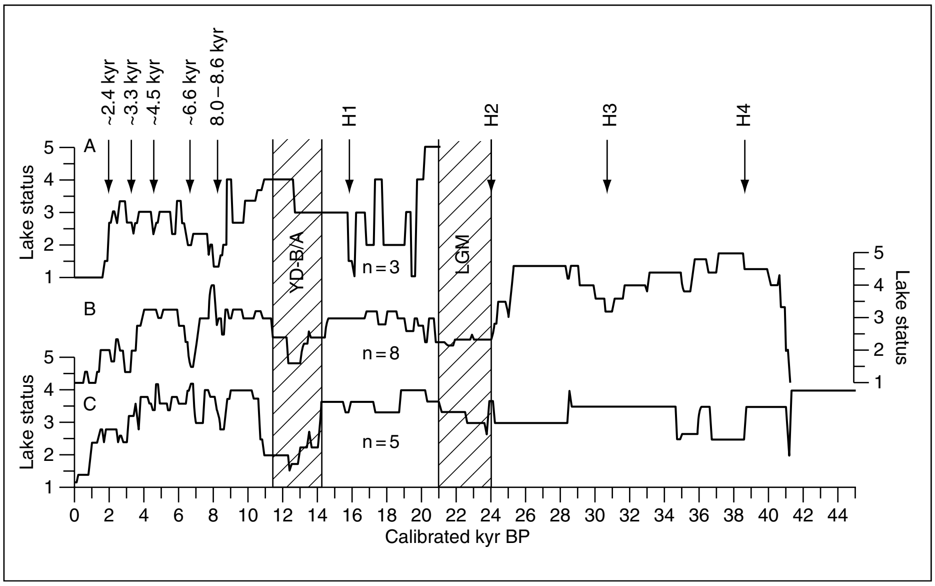

Fig. 6. Lake status records in 100-yr-intervals from selected sites within the Chinese desert belt. LGM = Last Glacial Maximum, YD-B/A = Younger Dryas/Bølling–Allerød events, H = Heinrich events, n = number of lakes involved in lake status coding. A: lakes north of the TPL without connection to glaciated areas since Holocene time, indicating East Asian summer monsoon influence; B: lakes north of the TPL with connection to glaciated areas of the Qilian Shan; C: lakes in the vicinity of the Tien Shan with connection to glaciated areas.

monsoon derived moisture. This conclusion is supported by the fact that only the two easternmost lakes (Fig. 1, nos 14 and 15), which were not connected to glaciated mountains, had already experienced a medium to high lake status since the Bølling – Allerød event as a result of increased local precipitation, while all other lakes were still beyond the direct influence of summer monsoon moisture supply. It remains uncertain whether the negative water budget was influenced by the insolation maximum at around 12 ka, which may have amplified sublimation of the glaciers, thus resulting in a reduced surface runoff. However, the intensification of the East Asian summer monsoon at about 13 ka prior but close to this maximum (Fig. 5A, F) predates the onset of the western branch (Indian monsoon) in western Tibet (Campo van and Gasse, 1993) by about 3 ka. This important event is documented by three lakes disconnected from glacier meltwater since the last termination (Fig. 6A). They all experienced high lake levels from 13 ka onward through the entire Younger Dryas spell up to the early Preboreal as a result of enhanced local summer monsoon precipitation. However, its strong impact on all glacier-connected desert lakes started a few centuries after the North Atlantic Younger Dryas (Figs. 5A, 6B, C), similar to the results from Lake Suigetsu (Nakagawa *et al.*, 2003) in Japan. This development is remarkably different from lake status changes during the LGM.

3.4 Lake Status Changes since the Start of the Holocene

The stabilisation of a high lake status during the Preboreal (9.5–11.5 ka) is in phase with the establishment of Siberian peatlands (Smith *et al.*, 2004), indicating sufficient effective moisture supply and warmer conditions to keep the desert lakes stable, biologically active but with a general trend to increasing salinity. Although the Holocene changes in lake status are still related to changes in glacier budget of the TPL and Tien Shan, the melt water flux remains of minor significance, which also explains the reduced lake extents during the Holocene compared with earlier times. More important for a positive water balance seems to be the northward shift of the summer monsoon boundary to some 100 km north of its modern limit (e.g. Yan and Petit-Maire, 1993), resulting in high local rainfall and the development of widespread fluvial/alluvial fans along the southern margin of the non-glaciated Gobi Altay mountains (Wünnemann and Hartmann, 2003).

The periodic lake status lows (Fig. 5A) since Holocene time indicate major changes in summer monsoon intensity, resulting in desiccation and thus drier conditions in the desert regions. Lake status records outside the glaciated mountains (Fig. 6A), compared with those from the Qilian Shan and the Tien Shan catchments (Fig. 6B, C) display differences in the timing of these events: Whereas a weak summer monsoon between 8.6–8.0 ka, well known as the 8.2 ka event, recorded in Greenland ice cores, at Bosten lake, Xinjiang (Wünnemann *et al.*, 2006) and on the TPL as well (Herzschuh *et al.*, 2006), all resulted in negative water budgets with only slight time lags, subsequent weaker phases lasting a few 100 years and centring at 6.6, 4.5, 3.3 and 2.4 ka no longer ran synchronously at TPL- (Qilian Shan) and Tien Shan-connected lakes. In our opinion the time lag of up to 500 years in lake status changes between lakes in the western and the eastern part of the study area documents the retarding effect of the summer monsoon influence in western China. However, moisture supply supplemented by the westwind system seems to have been a prominent trigger for lake status changes during the entire period under consideration.

The regional asynchronous precipitation patterns of the East Asian monsoon over China as reported for the Holocene Optimum (He *et al*., 2004) are not inconsistent with our results and support the assumption of generally enhanced precipitation in northern China between 10 and 7 ka. However, the standard deviations also show (Fig. 4B) that local conditions within the lake catchments played an important role at this period, resulting in locally varying lake status records but without masking the major trends of climate instability. Tectonic impacts on the fluvial systems and lacustrine basins, which may have induced significant changes in the hydrological cycles since Last Glacial are still unknown in detail. However, geological investigations on terraces and fluvial fans along the northern boundary of the TPL (Li *et al*., 1999) indicate that local displacements along the Qilian Fault system did not have any major impact on the hydrological systems, e.g. strong changes in river courses, during the past 50 ka.

Since about 4 ka all lakes have experienced a dramatic and continuous drop in lake status, which is also visible in other regions of the African – Asian dryland belt and seems to be a general phenomenon of reduced water supply along the monsoon pathways. It still remains to be clarified whether human impact has since become a controlling factor.

4. Conclusion

Lake status records from central Asian desert lakes indicate that changes in water budgets are strongly linked with global climate signatures. The interrelated processes of glacier dynamics, marine circulation pattern and monsoon variability during the Late Glacial cycle were the main triggers for the evolution of the desert lakes in north-western China in space and time.

Our lake status record, however, is closely related to changes in the regional precipitation pattern, while temperature variations may have played a minor role. Moisture availability was mainly controlled by two different air masses: the SE summer monsoon and the westerly winds. Despite their differences in water vapour sources and transport capacity, which might have influenced the effective moisture supply in different regions, our data imply that all investigated lakes responded synchronously in terms of water budget during the Last Glacial. The major reason for this synchronism is the fact that the lakes were connected with the glaciated mountain ranges, leading to sufficient meltwater supply which kept the lakes on high levels. This might be also the reason why the lakes did not dry up completely in periods of reduced water supply, when cold-dry climate conditions during the LGM and during short-term events, such as the Heinrich events and the Younger Dryas spell prevailed. Phases of low lake status promoted the exposure of fine-grained lacustrine deposits now being deflated by wind erosion and re-deposited as loess. Grain size records from the Loess Plateau confirm the coherence of low lake status and enhanced loess mobilisation quite well.

Since the last termination the global interplay between glacier development and the monsoon/westerlies over Asia lost its major impact on the water budgets of the desert lakes. Owing to the fact that summer monsoon related moisture supply during the Holocene period could not affect all desert lakes synchronously, influences by local catchment characteristics have more frequently overprinted regional climate signals. Despite the differences in lake status since the last 13 ka, however, major negative water budgets were still linked to global climate deteriorations around 8.6–8.0, 7.0–6.4, 4.8–4.4, 3.5–2.9 and 2.5–2.2 ka, documenting at least synchronisation on a larger scale. Differences in the timing of dry events in north-western China between the western and eastern part of the study area are due to the retarding influence of the summer monsoon and moisture control by the westwind system.

We conclude that lake development in arid China displays the influence of northern hemispheric circulation patterns much more significantly than any other factors such as tectonic events. Hence, the desert lakes are important archives with the potential to provide a valuable basis for the reconstruction of Asian monsoon system feedback mechanisms over China.

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3

Post-glacial climate variability and drought events in the monsoon transition zone of western China

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Abstract

Pollen assemblages, geochemistry, sedimentology, and lithology of a sample column collected from the Sanjiaocheng (SJC) section in a dry lake bed along the East Asian Monsoon margin document a very dry climate during the last glacial, a generally humid climate during the deglacial and Early Holocene, a dry climate during the Middle Holocene between 7.1 and 3.8 ka, and a humid but quite variable climate during the Late Holocene. A humid Early Holocene monsoon climate is also indicated by a well-developed Holocene soil formed across the Loess Plateau during the period. Our study, like many global climate change models, suggests that millennial-scale climate oscillations with a periodicity of about 1500 years occurred throughout both wet and dry periods of the Holocene. These oscillations were pervasive and persistent following the last glacial. Multi-centennial cycles are evident in the pollen records dating to the Early Holocene. Ten dry intervals indicating a weak summer monsoon at 0–0.5, 1.2–1.9, 2.4–3.4, 5.0–7.1, ~7.8, 8.3–8.8, 9.2–9.7, 10.4–11.2, 11.6–12.8, and 13.3–13.8 ka are documented by multi-proxies at the SJC section. Long, intense dry events, such as at around 1.0, 3.0, and 5–7 ka, are also recorded by interruptions in Holocene soil development. Three less-intensive dry episodes at around 8.5, 9.5, and 10.0 ka in the humid Early Holocene that normally are not evident in pure eolian loess–soil sequences were documented at a high-resolution fluvial loess–soil sequence. Our study suggests cold climate events in the North Atlantic region are coeval with dry climate events (indicating a weak summer monsoon) along the East Asian Monsoon margin following the last glacial. This supports the hypothesis that Holocene climatic events are strongly correlated throughout at least the Northern Hemisphere.

1. Introduction

Climatic variations at millennial to centennial time scales have been detected in oceanic and ice core records during the last glacial (Bond *et al.*, 1992; Johnsen *et al.*, 1992; Dansgaard *et al.*, 1993) and earlier in the Quaternary (Oppo *et al.*, 1998; McManus *et al.*, 1999). Atlantic deep ocean records indicate typical interglacial and full glacial periods were relatively stable, while transitional periods were quite unstable (McManus *et al.*, 1999). Abrupt climatic changes during the last glacial are also well documented in Chinese loess sequences (Porter and An, 1995; Ren *et al.*, 1996; Chen *et al.*, 1997) and cave speleothem records (Wang *et al.* 2001; Yuan *et al.*, 2004) in both East Asian and Indian monsoon-dominated regions. However, climatic variations during the current interglacial (Holocene) most likely have different boundary conditions and forcing mechanisms than those of the last glacial. Research has also shown that the Holocene climate was also quite variable on millennial and centennial time scales at high latitudes (Bond *et al.*, 1997; Bianchi and McCave, 1999). Variations with similar periodicities to those detected in the Greenland ice cores (O'Brien *et al.*, 1995) reflect a terrestrial aridity record connected with high dust-aerosol originating in arid central Asia. Six Holocene cooling and/or drought events are apparently correlated in many parts of the world (Mayewski *et al.*, 2004), providing evidence of global centennial- to millennial-scale climatic variability and abrupt changes during the Holocene.

Understanding climatic variability in monsoon Asia is critical since the region contains 60% of the world population. It is well known that the Asian monsoon has seasonal and decadal variability, resulting in floods in south China and severe droughts in north China, but it may also be variable at centennial and millennial scales. Speleothem studies indicate that shifts in the Asian monsoon generally reflect insolation changes, although there were small asymmetric events in southwest China during the Holocene warm period (Wang *et al.*, 2005). This is not surprising as the monsoon often exhibits variability at its margins. It has become evident that two or three reductions in the monsoon occurred in the Loess Plateau during the Holocene (Huang *et al.*, 2000, 2002), and a strong mid-Holocene drought event was previously documented by lake margin studies (Chen *et al.*, 2003). We also found that strong millennial-scale changes occurred in the East Asian Monsoon margin during the Holocene (Chen *et al.*, 2006), with multi-centennial scale changes occurring in the Early Holocene (Chen *et al.*, 2001). In this paper, after summarizing published data and adding new data from lake sediment and Holocene loess–soil sequences, we show that centennial- to millennial-scale climatic variability and drought events

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at the monsoon margins occurred throughout the deglacial period. Our study further demonstrates that the Holocene summer monsoon along the margin of the Loess Plateau and southern Mongolian Plateau not only changed remarkably, as has been suggested (Gasse and Van Campo, 1994), but also reflects periodic rapid climate change events similar to those that occurred during the last glacial period.

2. Geographical Setting

Our study area on the East Asian summer monsoon margin is bounded on the south and southwest by the Qinling Mountains and the Qilian Mountains bordering the high-altitude Tibetan Plateau, the Mongolian Plateau to the north, and the Luliang-Taihang Mountains on the east (Fig. 1). In the northern part of our study area lie some of the major dune fields of China, including the Badain Jaran and Tengger deserts and the Mu Us and Otindag sandy lands. These deserts form the natural boundary of the Asian summer monsoon and every year produce huge amounts of dust and silt that are deposited in the Loess Plateau to the south of the study area. Annual precipitation decreases from near 700 mm to less than 50 mm across the area from the Loess Plateau in the southeast to the Badain Jaran Desert in the northwest. Correspondingly, vegetation changes from forest, to forest/grass, to typical steppe, and then to typical desert. In the summer half of the year, the Asian summer monsoon brings 80% of the annual precipitation to the area, resulting in flourishing regional vegetation growth and high productivity. In the winter half of the year, on the other hand, strong cold air blows in from the Mongolian High, bringing dust and silt to the Loess Plateau and points further east and south. As a result, the typical climate is warm and moist in summer and cold and dry in winter. Because the study region is at the summer monsoon margin, precipitation and vegetation are highly variable, a feature evidenced historically by periodic severe droughts. Long-term changes in this climatic and vegetation background likely had a marked influence on the developments of Paleolithic and Neolithic cultures in the region.

The SJC section is at the margin of Lake Zhuyeze, at the end of the Shiyang River drainage (Fig. 1). The drainage is 300 km long, with an area of 41,163 km^2 and lies on the westernmost margin of the summer monsoon. The river originates from the northern side of the Qilian Mountains,

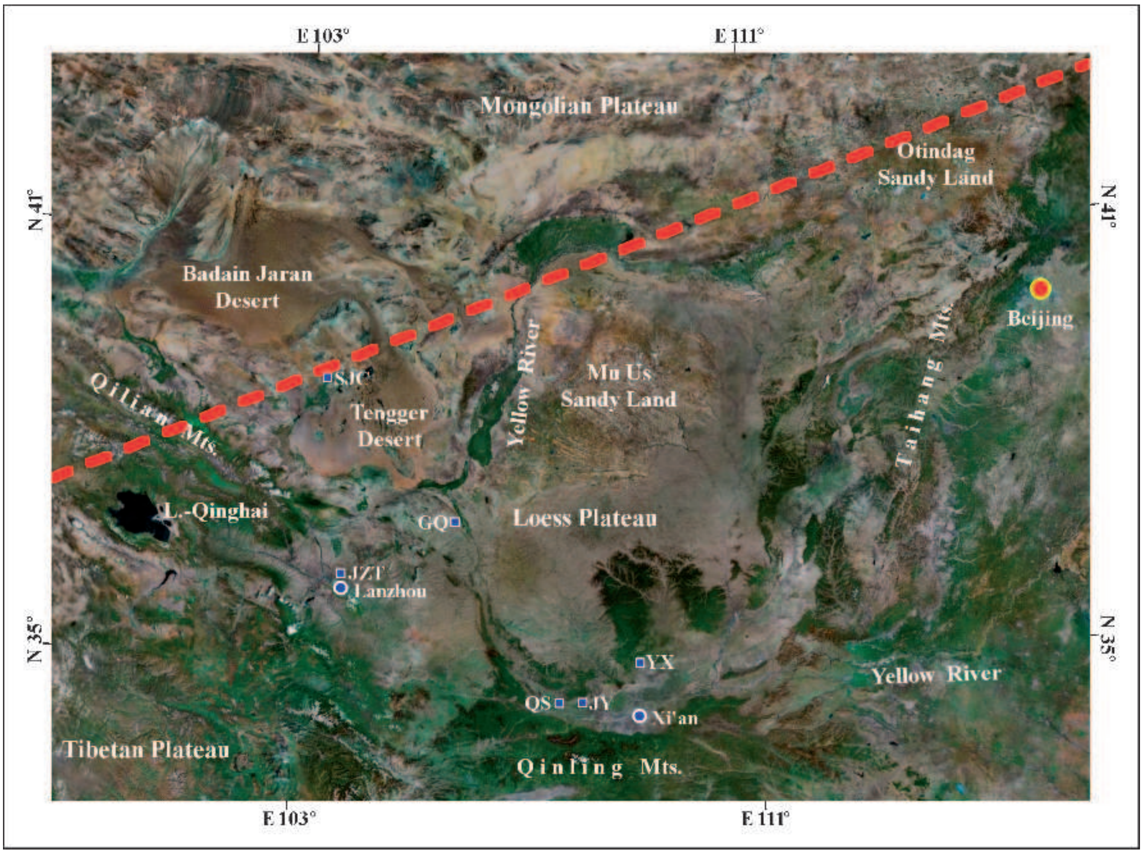

Fig. 1. Remote sensing image of landscape and vegetation cover along the East Asian Monsoon margin on the southern Mongolian Plateau and central north China, where most late Paleolithic and Neolithic culture sites discussed in this volume are located. The red dashed line indicates the location of the modern East Asian summer monsoon front. Sites referenced in the text are marked by filled squares. SJC, Sanjiaocheng; GQ, Guanqiao; YX, Yaoxian; JZT, Jiuzhoutai; JY, Jiangyang; QS, Qishan.

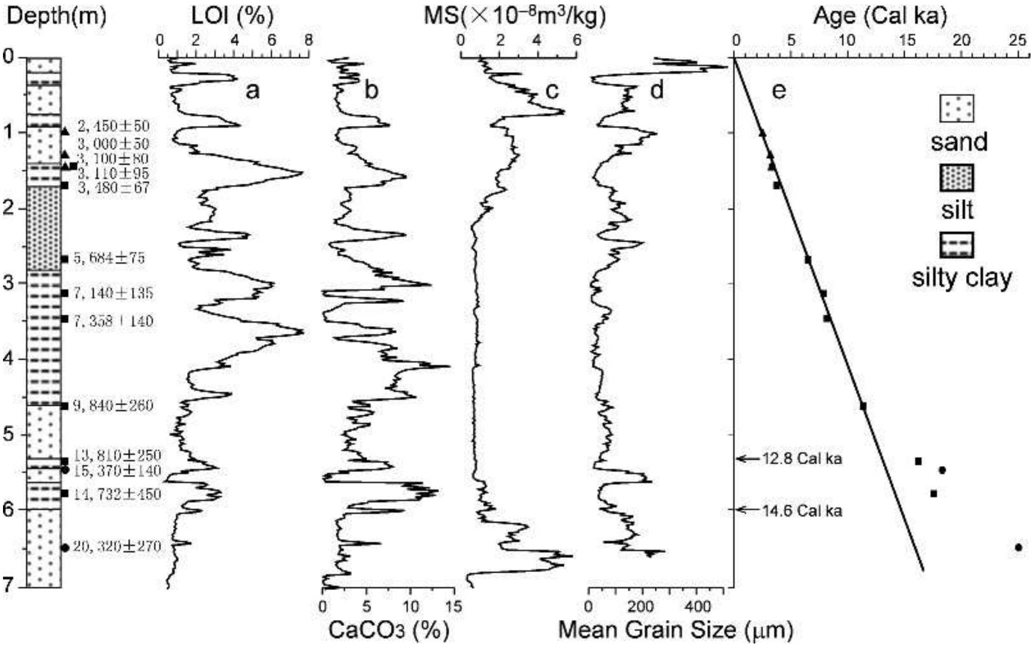

Fig. 2. Stratigraphy and chronology of the SJC section. The carbon reservoir corrected radiocarbon dates (^{14}C yr BP) are marked beside the lithological bar (filled square, ^{14}C age for bulk organic matter; filled triangle, ^{14}C age for charcoal; filled dot, ^{14}C age for pollen concentration remains). The relationship of calibrated ages with depth (e) is nearly linear during the Holocene. Loss-On-Ignition (LOI) content (a), $CaCO_3$ content (b), mass magnetic susceptibility (c), and mean grain size (d) with depth are also shown.

on the northwest margin of the Tibetan Plateau, and flows northward through a fluvial/alluvial fan plain and gobi. At its terminal end, the river forms Lake Zhuyeze between the Tengger and Badain Jaran deserts (Fig. 1). The river water is supplied primarily by the summer monsoon, with only 3.8% coming from glaciers and snow (Chen and Qu, 1992). The studied section (Fig. 2) is a 700-cm-deep excavation at an elevation of 1320 m, latitude 39°00′38″ N and longitude 103°20′25″ E on the western margin of Lake Zhuyeze. The section consists of Holocene lacustrine clay–silt and silt and sand and is described by Chen *et al.* (2006) in detail. Because of recent desertification, the present land surface is covered by eolian sand. Samples were taken every 2 cm (producing a ∼50 yr/sample time resolution) at the section for analyses of various environmental proxies, including pollen, loss-on-ignition (LOI), calcium carbonate ($CaCO_3$), magnetic susceptibility (MS), grain size (GS), and organic carbon isotope. Twelve samples were taken for radiocarbon age estimates at lithological boundaries and from organic-rich layers (Fig. 2).

Loess layers (weak pedogenic layers) are known to have interrupted Holocene paleosol formation in the Loess Plateau, forming alternating layers of Holocene soil and loess (Liu *et al.*, 1985; Zhou, 1995). We studied several Holocene loess and soil sections across the Loess Plateau (Fig. 1). The Qishan (QS) section is at Nanguanzhuang village of Qishan County at latitude 34°27′ N and longitude 107°46′ E. The mean annual temperature there is 12° C and yearly precipitation is 629 mm (Huang *et al.*, 2002). The JiangYang (JY) section is near Famensi, Fufeng County at latitude 34°28′ N and longitude 107°53′ E. Annual precipitation is 650–700 mm and the mean annual temperature is 12° C in this area of the southern Loess Plateau. The Yaoxian (YX) section is near Yaoxian County at latitude 34°53′ N and longitude 108°50′ E. It lies in the central Loess Plateau with annual precipitation of 700 mm and an average annual temperature of 13° C. The fourth Holocene loess section, Jiuzhoutai (JZT) section, is near the city of Lanzhou at latitude 36°06′ N and longitude 103°47′ E. It is on the western edge of the Loess Plateau with an annual precipitation of 320 mm and a mean annual temperature of 9° C. These four sections are pure eolian loess–soil sections. The Guanqiao (GQ) section, at latitude 36°58′25″ N and longitude 105°46′48″ E, on the very northern margin of the Loess Plateau, is close to northern deserts and has an average annual precipitation of 200 mm and a mean annual temperature of 4° C. The section is situated on the first terrace of a Qingshui River tributary, and its formation was strongly influenced by river water. The lithology consists of wetland soil and silt–sand deposits.

3. Laboratory Methods

Standard techniques were employed for pollen extraction and analysis with some modifications (Li *et al.*, 1995). For silty clay, 60 to 80-g samples were taken for laboratory analysis, while for silt and sand, 100 to 120-g samples were taken. In samples with good preservation, about 300 pollen grains and spores were counted, while 10 slides were counted if the pollen concentration was low.

LOI was measured by heating samples to 450° C and determining percentage weight difference before and after heating. $CaCO_3$ content was measured using the Calcimeter method of Bascomb (1961). Mass MS was measured following Walden *et al.* (1999) by averaging three measurements using a Bartington Instruments Magnetic Susceptibility Meter with a dual frequency sensor. GS samples were pretreated by adding 15% HCl to remove $CaCO_3$ and then boiling in H_2O_2 to remove organic matter. GS was measured using a Malven Master Sizer 2000 in mode of 0.2–2000 μm range.

Optically stimulated luminescence (OSL) dating applied to eolian sequences has been proved effective in many studies because it is applied directly to the mineral component of the sediment (Stokes *et al.*, 1997; Murray and Olley, 2002; Li *et al.*, 2002). The OSL dating procedures used here follow the standard for eolian deposits (Li *et al.*, 2002), with some modifications for loess–paleosol sequences. Coarse quartz grains, 63–150 μm interval, were prepared from raw loess or paleosol samples by sieving, heavy liquid separation, and hydrofluoric acid (HF) etching. Separated quartz grains were measured in a thermoluminescence (TL)/OSL reader to determined equivalent dose (De) by the single aliquot regeneration method (SAR) (Murray and Wintle, 2000). The environmental dose rate created by radioactive elements in the raw sample was measured with a variety of techniques. Thick source alpha counting (TSAC) was used to obtain contributions from the uranium (U) and thorium (Th) decay chains, while the potassium (K) content was measured by X-ray fluorescence (XRF). U and Th concentrations and K contents were also determined directly by means of neutron activation analysis (NAA). All measured results were converted to alpha, beta and gamma dose rates according to a conversion factor following Aitken (1985). The calculated dose rate contributed by cosmic rays was calculated based on the burial depth and the altitude of the sampling site (Prescott and Hutton, 1994). The water content was determined by using the ratio of water weight to the dried sample weight, obtained from sample weights before and after drying in an oven.

4. Result and Discussion

4.1 Chronology Sequence

Radiocarbon dates were measured by both the conventional ^{14}C method on five bulk organic matter samples and the accelerator mass spectrometer (AMS) on picked charcoal samples. Table 1 lists all of the measured dates from the SJC lacustrine section. Radiocarbon ages were determined by subtracting a 530-year reservoir effect identified by comparing two dates at 1.45 m deep and were calibrated into calendar years using the Intcal04 program (Reimer *et al.*, 2004). All ages in the text are given in calendar years unless otherwise noted. The upper 4.6 m of sediment was deposited during the Holocene, and the calibrated ages have an almost linear relationship with the depth for this period (Fig. 2). We use the age sequence established by Chen *et al.* (2006) for the Holocene period. However, all four radiocarbon dates below 4.6 m deviate from the linear relationship (Fig. 2). The sediment at the

Table 1. List of the radiocarbon dates at SJC section.*

Sample no.	Lab no.	Depth (m)	Material	Original dates (^{14}C yr BP)	Reservoir corrected age (^{14}C yr BP)	Calibrated age (Cal yr BP)
SCJ-C03	Beta-135877	1.00	Charcoal	2,450 ± 50	2,450 ± 50	2,530 ± 170
SJCH02	LZU98-20	1.30	Ash charcoal	3,000 ± 50	3,000 ± 50	3,200 ± 120
SCJ-C04	Gifa-100272	1.45	Charcoal	3,110 ± 80	3,110 ± 80	3,325 ± 115
Sjch3	LZU98-21	1.45	Bulk organic	3,641 ± 95	3,111 ± 95	3,330 ± 120
Sjch4	LZU98-22	1.72	Bulk organic	4,010 ± 67	3,480 ± 67	3,740 ± 100
Sjch5	LZU98-23	2.66–2.72	Bulk organic	6,214 ± 75	5,684 ± 75	6,480 ± 130
Sjch6	LZU98-24	3.13	Bulk organic	7,670 ± 135	7,140 ± 135	7,995 ± 165
Sjch7	LZU98-25	3.45	Bulk organic	7,888 ± 140	7,358 ± 140	8,175 ± 145
Sjch8	LZU98-26	4.70	Bulk organic	10,374 ± 260	9,844 ± 260	11,275 ± 535
Sjch9	LZU98-27	5.40	Bulk organic	14,340 ± 250	13,810 ± 250	16,450 ± 400
SJC-C11	Beta-142800	5.50	Pollen concentration remains	15,900 ± 140	15,370 ± 140	18,735 ± 105
Sjch10	LZU98-28	5.80	Bulk organic	15,262 ± 450	14,732 ± 450	17,850 ± 700
SJC-C21	Beta-142801	6.50	Pollen concentration remains	20,850 ± 270	20,320 ± 270	24,350 ± 400

[*] Original dates were calculated using a half-life of 5,568 years, with a stable carbon isotope correction. The carbon reservoir effect for the bulk organic and pollen concentration samples is estimated to be 530 years.

bottom of the SJC section below 6.0 m is pure eolian sand with a cross-bedded structure and fluvial silt–sand interbedded with silt and silt–clay lake sediments from 6.0 to 4.6 m. This lowest part of the section indicates that the paleolake was almost dry during the last glacial maximum (Shi *et al.*, 2002). In recent cores we collected from the center of the paleolake, we also found that most of the lake was covered by a few meters of eolian sand during the last glacial (unpublished data). The two reversed dates at 5.5 and 5.8 m may be the result of marked soil erosion during the deglacial under unstable land surface conditions. The age of 24,350 Cal yr BP at a depth of 6.5 m supports the notion that the basal eolian sand was deposited during the last glacial maximum. We therefore conclude that the layers of lacustrine silt–clay and silt (Fig. 2) were deposited during the deglacial. A rapid climate event model may be a reliable way to solve chronology problems resulting from uncertainty in different dating methods (Bjorck *et al.*, 1998). Since unstable climatic events and millennial variation in north China can be globally correlated during the last glacial (Porter and An, 1995; Chen *et al.*, 1997), these boundary ages may provide accurate age controls for rapid climatic changes during the last glacial. We therefore adopt the Bφlling–Allerφd boundary ages of the Chinese speleothem oxygen isotope record (Wang *et al.*, 2001) to be the ages of the two silt–clay layers at 14.6 and 12.8 ka (Fig. 2). Between these event ages, a linear average deposition rate is applied to each sample, while for the bottom sand we use the same deposition rate as that between 4.6 and 5.2 m.

All of the OSL dates for the loess sections (Fig. 3) are shown in Table 2. Most OSL dated samples were taken from the boundaries of Holocene soils and loess in order to capture drought events. The OSL dating results indicate three periods of high dust deposition following the Early Holocene: ~7–5 ka at the JY and QS sections, ~3.7–2.7 ka at the JZT and YX sections, and ~1.3–1.0 ka at the QS, JZT, and YX sections (Fig. 3). At most eolian loess sections in the Loess Plateau, the most well-developed soil apparently formed during the Early Holocene. However, we found this Early Holocene soil was interrupted by three layers of light-colored dust at soil sections on low river terraces frequently influenced by fluvial processes. The GQ section is a good example (Fig. 3). There are three layers of sand dating to ~8.0, ~9.5, and ~10 ka in the section, although more OSL dates are needed to refine the chronology. The top loess is OSL dated to ~6.8 ka (Fig. 3), indicating a markedly arid environment and eolian deflation after the Early Holocene.

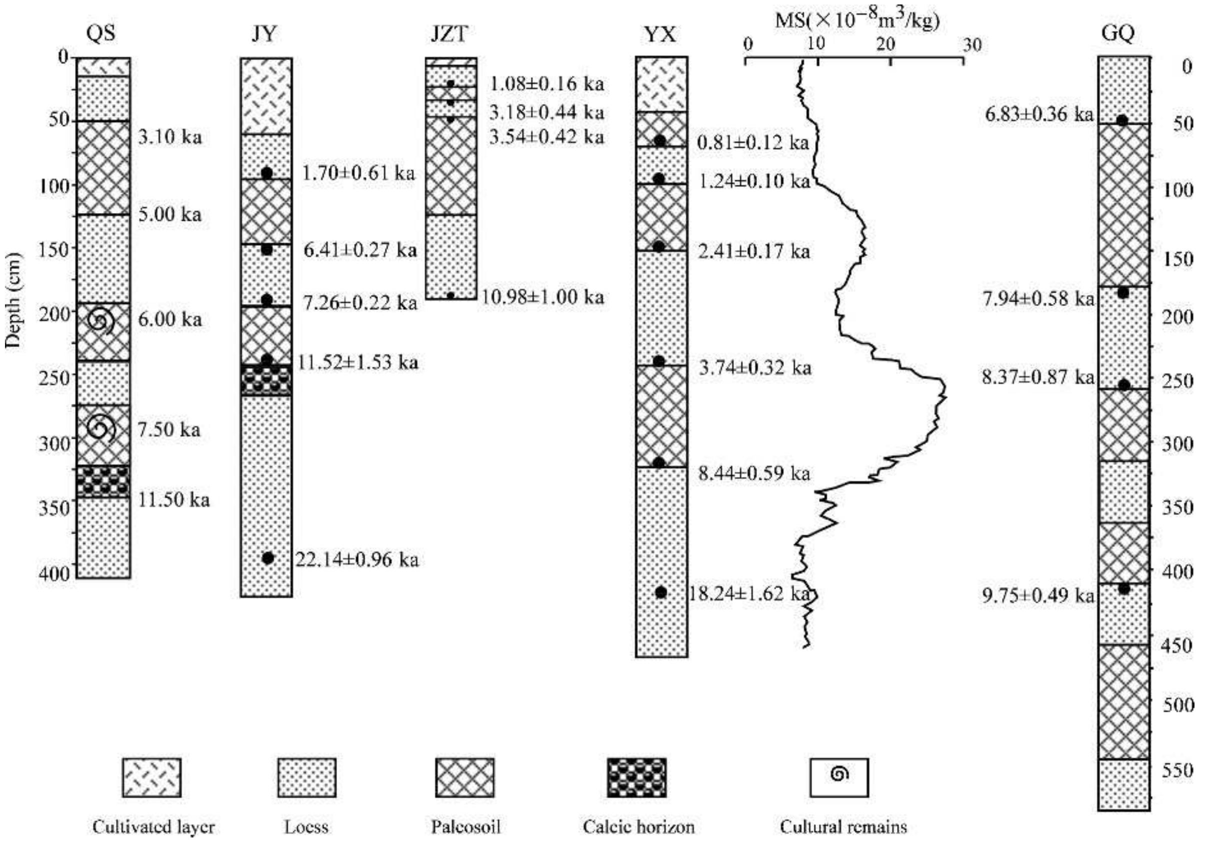

Fig. 3. Holocene loess–soil sequences in the Loess Plateau. OSL date positions at the sections are marked with dots on each section bar, with OSL dates in thousand years (ka) displayed beside the section bars. Mass magnetic susceptibility (MS), a proxy of pedogenesis and the interplay between soil development and dust deposition, of the YX section is also shown. The Holocene soil sequence at Qishan (QS) section follows Huang et al. (2000).

Table 2. OSL dates at different Holocene loess–soil sections across the Chinese Loess Plateau.

Sample	Sampling point	Equivalent dose (Gy)	Aliquot	α Counting rate (/ks)[a]	K content (%)	Water content (%)[b]	Cosmic dose rate(Gy/ka)[c]	Dose rate (Gy/ka)	Age (ka)
GQ50	Bottom of loess	25.01 ± 0.63	20	10.52	2.112	7.8	0.22	3.66 ± 0.18	6.83 ± 0.36
GQ180	Top of loess	28.54 ± 0.80	20	11.50	2.147	13.0	0.22	3.59 ± 0.25	7.94 ± 0.58
GQ250	Bottom of loess	35.15 ± 1.68	10	13.80	2.094	15.3	0.20	4.04 ± 0.16	8.73 ± 0.87
GQ410	Top of loess	39.48 ± 1.28	14	13.41	2.051	10.1	0.18	4.05 ± 0.16	9.75 ± 0.49
YX70	Bottom of soil	3.28 ± 0.47	8	12.76	2.35 ± 0.05	8.2	0.22	4.04 ± 0.27	0.81 ± 0.12
YX110	Bottom of loess	5.33 ± 0.14	9	14.35	2.58 ± 0.05	7.3	0.22	3.70 ± 0.31	1.24 ± 0.10
YX165	Bottom of soil	9.66 ± 0.16	15	13.57	2.19 ± 0.05	9.8	0.22	3.99 ± 0.27	2.41 ± 0.17
YX255	Bottom of loess	15.93 ± 0.47	8	13.36	2.62 ± 0.05	7.9	0.20	4.25 ± 0.30	3.74 ± 0.26
YX340	Bottom of soil	31.41 ± 0.76	12	11.37	2.24 ± 0.05	9.2	0.19	3.72 ± 0.25	8.44 ± 0.59

Sample	Sampling point	Equivalent dose (Gy)	Aliquot	U (ppm)	Th (ppm)	K content (%)	Water content (%)	Cosmic dose rate (Gy/ka)	Dose rate (Gy/ka)	Age (ka)
YX430	In Malan loess	50.91 ± 1.29	13	1.38 ± 0.13	10.4 ± 0.24	1.74 ± 0.11	6.3	0.18	2.79 ± 0.24	18.24 ± 1.62
JY100	Bottom of loess	5.38 ± 0.46	8	2.67 ± 0.10	14.11 ± 0.31	1.90 ± 0.09	15.8	0.22	3.23 ± 0.19	1.70 ± 0.16
JY160	Top of loess	20.68 ± 0.65	10	2.90 ± 0.11	12.62 ± 0.28	1.89 ± 0.08	16.5	0.20	3.33 ± 0.30	6.21 ± 0.27
JY200	Bottom of loess	26.86 ± 0.65	9	2.87 ± 0.09	13.20 ± 0.31	2.19 ± 0.09	17.5	0.20	3.73 ± 0.33	7.20 ± 0.22
JY250	Bottom of soil	43.92 ± 1.65	14	2.77 ± 0.10	14.11 ± 0.32	2.26 ± 0.10	12.8	0.18	3.81 ± 0.38	11.52 ± 1.53
JY400	In Malan loess	73.32 ± 3.18	10	2.63 ± 0.10	11.92 ± 0.21	1.80 ± 0.07	12.6	0.15	3.31 ± 0.31	22.14 ± 0.96
JZT25	Bottom of loess	4.01 ± 0.49	9	2.65 ± 0.10	12.31 ± 0.28	1.95 ± 0.09	1.2	0.30	3.73 ± 0.27	1.08 ± 0.16
JZT40	Top of loess	11.32 ± 1.21	7	2.98 ± 0.11	12.30 ± 0.28	1.68 ± 0.08	1.7	0.30	3.57 ± 0.31	3.18 ± 0.44
JZT55	Top of soil	13.74 ± 0.93	7	3.34 ± 0.12	12.50 ± 0.29	1.92 ± 0.09	2.4	0.29	3.88 ± 0.38	3.54 ± 0.42
JZT200	In Malan loess	37.96 ± 0.19	14	3.34 ± 0.10	11.61 ± 0.22	1.82 ± 0.08	0.7	0.24	3.66 ± 0.32	10.98 ± 1.00

[a] The α counting rate is for a 42 mm diameter ZnS screen.

[b] The error for the water content is estimated at ± 5% during the dose rate calculation.

[c] The error for the cosmic ray dose rate is estimated as ± 0.02 Gy/ka during the dose rate calculation.

4.2 Environmental Changes since the Last Glacial Maximum: An Example from the Shiyang River Drainage

Because MS is sensitive to oxidization or deoxidization conditions in lake sediments, we expect that high MS values indicate increased eolian input into a shallow lake or even a dry lake bed, while low MS values should be consistent with lacustrine deposition. High MS (Fig. 2a) is found before 14.8 ka (6.1 m deep) and after 5 ka (2.0 m deep) at the SJC section, while it is generally low in the middle of the section. The MS sequence indicates that an eolian environment prevailed during the last glacial period at Lake Zhuyeze, an interpretation supported by other cores from the center of the lake (unpublished data) and by previous studies (Pachur *et al.*, 1995). Eolian input into the lake decreased after about 14 ka and was reduced to low levels between 14 and 6 ka. Increasing MS values after 5 ka indicate another period of increased eolian sand/dust into the lake, probably derived from activation of Tengger Desert and Badain Jaran Desert dunes. Mean GS reflects a high degree of variance from silt clay to coarse sand. Fine GS occurs in the lacustrine layers and coarse GS in either eolian sand layers or lacustrine silt–sand layers (Fig. 2). These size changes coincide with lithological changes. Both the MS and the GS proxies indicate that the paleolake was dry before 14.8 ka, stable until 7 ka, then alternated between a permanent and shallow-water lake.

Over 50 plant taxa were identified in the pollen assemblage, but only the principal taxa are shown in Fig. 4. Based on the relationship between pollen assemblages and the distribution of modern vegetation in the drainage (Zhu *et al.*, 2003; Cheng *et al.*, 2004), all pollen taxa can be divided into three broad ecological groups (Fig. 5): (1) taxa representing high-elevation (montane) vegetation, especially that from forest zones, consisting primarily of *Sabina*, *Picea*, *Pinus*, and others; (2) regional vegetation taxa, derived from steppe vegetation from across the whole drainage basin, such as Rosaceae, Leguminosae, Rhamnaceae, Poaceae, Compositae, Chenopodiaceae, Cyperaceae, *Artemisia*, and *Polygonum*; and (3) taxa from the lower reaches of the drainage. These are primarily xerophytes from the desert vegetation zones and marsh vegetation from the lake margin, including *Nitraria*, *Calligonum*, *Ephedra*, Zygoghyllaceae, Plumbaginaceae, Elaeagnaceae, and *Typha*. Little pollen is present in samples dating to before 14.3 ka. After 14.3 ka, there are three principal stages of vegetation change reflected in a summary figure of the main vegetation types in the drainage system (Fig. 5). Conifer pollen, constituting around 80%, is dominant in the deglacial and Early Holocene periods between 15 and 7 ka, while regional herb and local shrub pollen, mainly consisting of xerophyte plant pollens such as *Nitraria*, Chenopodiaceae, and *Artemisia*, is dominant between 7.1 and 3.8 ka. The Late Holocene after 3.8 ka is characterized by high percentages of conifer and regional plant pollen (Fig. 5). Pollen diversity, a proxy of biodiversity, also reflects this sequence.

Four stages of climatic and environmental changes can be inferred from the multi-proxies, especially from the pollen assemblage.

Dry last glacial (before 15 ka) – The climate was very dry during the last glacial period. Eolian sand with cross-bedded strata is found at the bottom of the SJC section. Mean GS, with a typical dune sand distribution mode, is generally very coarse with a mean diameter around 200 μm (Fig. 2). High mass MS indicates that the section site may have been totally dry during the last glacial period. Limited or no pollen in the last glacial samples also indicates that a typical desert environment was present at that time and that no river water brought montane vegetation pollen to the site. Recent cores from across the paleolake floor indicate there was a general eolian dune sand cover over the lake bed during the last glacial, as reported by Pachur *et al.* (1995). It can be deduced that the two main dune fields of the Tengger and Badain Jaran deserts (Fig. 1) may have merged. OSL dates at the JY and YX sections in the central Loess Plateau (Fig. 2) show dust (loess deposition) prevailed at 18–22 ka and lasted until the initiation of Holocene soil development.

Humid deglacial and Early Holocene (14.6–7.1 ka) – In contrast, pollen from the deglacial is well preserved, despite the coarse GS in some layers, particularly those dating to around 13.5 ka. Conifer pollen percentages increase from the deglacial through the Early Holocene until ~7 ka, although they are low and variable in the early stage of the deglacial (Figs. 4 and 5). Regional vegetation pollen percentages are stable and low in this period. Pollen concentrations, especially montane pollen concentrations, and pollen diversity are relatively high (Fig. 5), indicating favorable conditions for plant growth throughout the drainage. The pollen assemblage suggests the montane forest zone expanded on the north slope of the Qilian Mountains, with greater runoff causing greater transport of tree pollen (Zhu *et al.*, 2002; Zhu *et al.*, 2003). Since meltwater from glaciers and snow was a minimal component of the total runoff (Chen and Qu, 1992), the high runoff in the deglacial and Early Holocene likely did not result from a warm climate, but rather from high precipitation under more intense summer monsoon conditions. Low MS and fine GS indicate a stable lake environment during this period. Conifer pollen during the Younger Dryas (YD) cold event is no different from preceding or following periods, although *Sabina* pollen percentages, a proxy of cold and dry climate in the drainage (Zhu *et al.*, 2002), constitute a higher portion of the conifer pollen assemblage. It is possible that during the YD the *Sabina* forest in the mountains on the margin of the Tibetan Plateau expanded, while the *Picea–Pinus* forest shrank, resulting in no net change in total conifer pollen percentages. In the Loess Plateau, intense pedogenesis occurred during the early Holocene (Porter, 2001; Huang *et al.*, 2002). In our dated loess sections (Fig. 4), well-developed Holocene soils occur at the base of the Holocene loess–soil sequence. This evidence of a humid Early Holocene climate along the monsoon margin coincides with monsoon variations documented by speleothem records for the Indian monsoon (Yuan *et al.*, 2004; Wang *et al.*, 2005) and by peat cellulose records for the East Asian summer monsoon (Hong *et al.*, 2005).

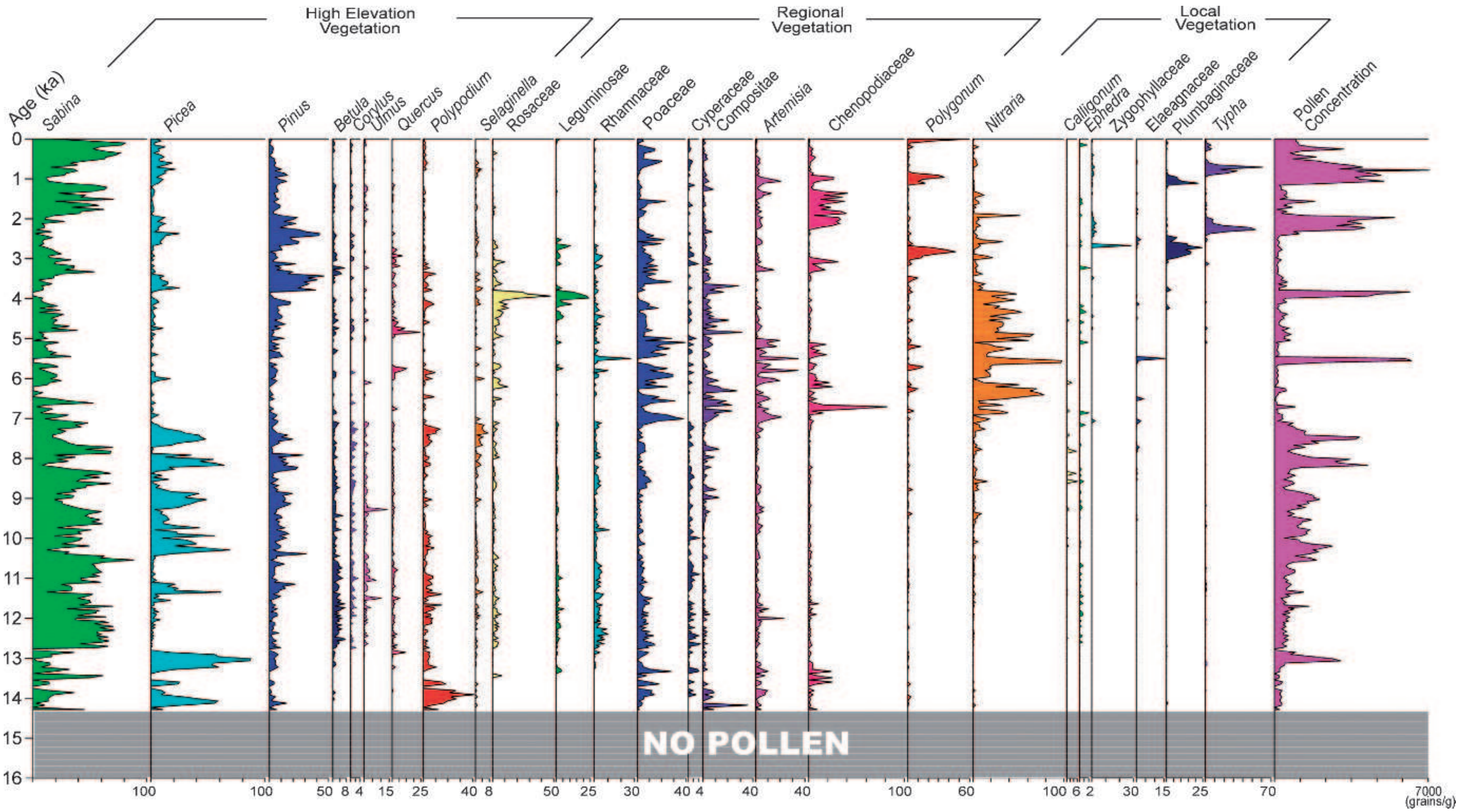

Fig. 4. Pollen percentage diagram and pollen concentrations at the SJC section since the last glacial, plotted with calibrated ages.

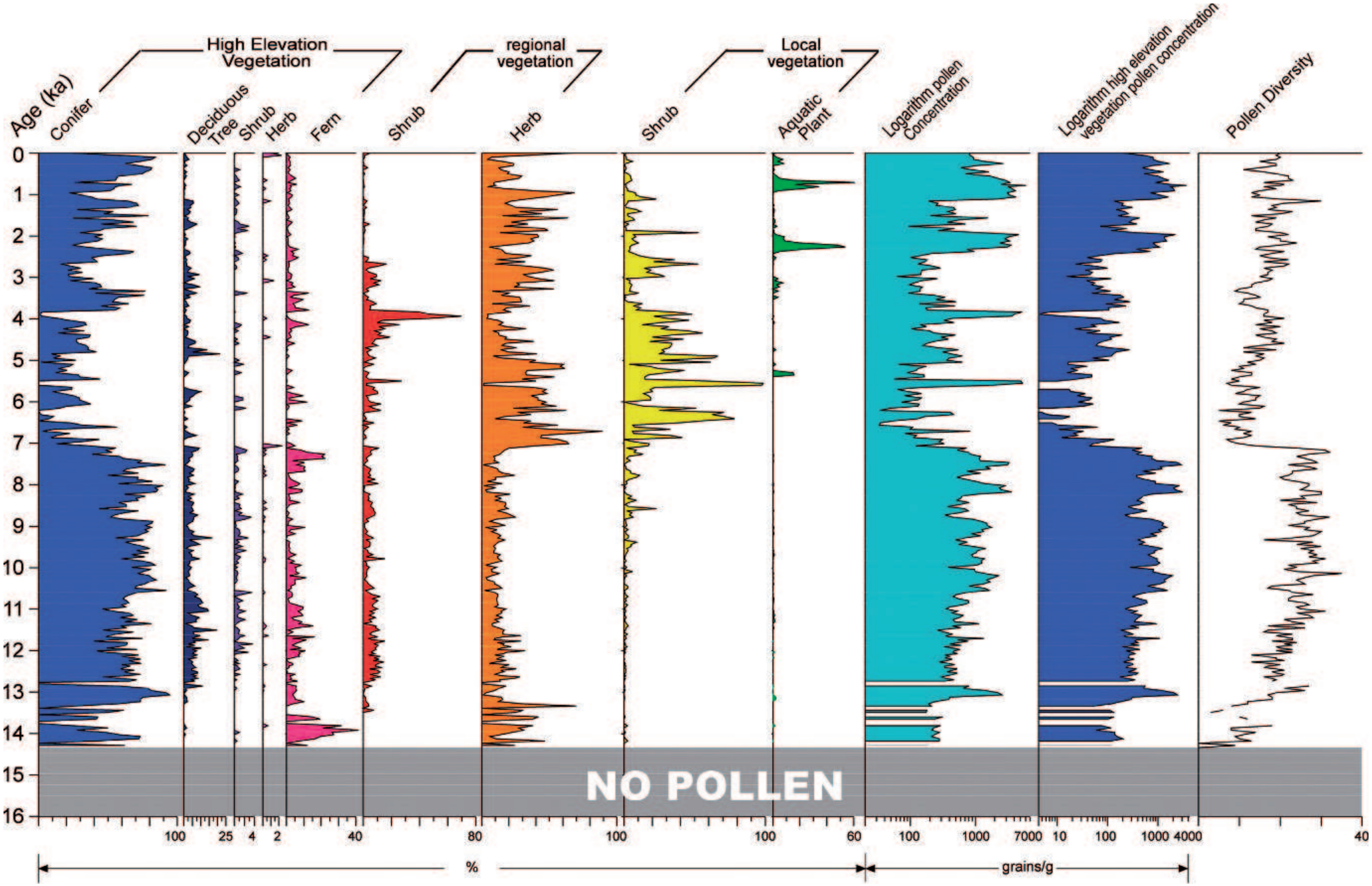

Fig. 5. Pollen diagram presented as the summary of ecological groups. The total pollen concentration, the high-elevation vegetation pollen concentration, and a pollen diversity index, a proxy of biodiversity, are also shown.

Dry mid-Holocene (7.1–3.8 ka) – During this period, desert and steppe shrubs and herbs were dominant. Low pollen concentrations suggest open vegetation cover. The forest belt was reduced and shifted to higher elevations in the Shiyang River drainage. The lowlands were covered primarily by steppe desert and desert vegetation. Very high *Nitraria* representation and the lack of other pollen types suggest the lake surface area was markedly reduced between 5.6 and 5.4 ka. Two corresponding pollen concentration peaks are due primarily to increases in local xerophyte pollen (Fig. 4). The driest interval was from 7.0 to about 5.0 ka, as evidenced by very low pollen concentrations, especially those for high-elevation taxa (Fig. 5). Low lake levels or complete desiccation in the Alashan Plateau, part of the southern Mongolian Plateau (Chen *et al.*, 2003), also document a dry climate during this period. During the Middle Holocene, soil formation was interrupted by high eolian dust input in the central Loess Plateau (Huang *et al.*, 2000; Li *et al.*, 2003). A dated Holocene soil section (JY section) at Fufeng, in the central Loess Plateau, shows an interruption of Holocene soil formation around 7.2–6.4 ka (Fig. 3). Both a decrease in the strength of the Asian summer monsoon (Wang *et al.*, 2005) and an increase in temperatures during the mid-Holocene megathermal period (Shi *et al.*, 1994) may have resulted in a mid-Holocene drought along the margin of the summer monsoon, as in the Yanhaizi Lake record in the Erdos Plateau (Chen C.T.A. *et al.*, 2003).

Humid, but variable, Late Holocene (3.8–0 ka) – Conifer-dominated forests expanded again during the Late Holocene in the Shiyang River drainage (Fig. 5). The environment was relatively wet compared to the mid-Holocene, but variations in pollen concentration and carbonate content (Figs. 4 and 6) indicate an alternation of dry and humid climates. High MS values (Fig. 2) reflect a strong eolian input into the lake. Coarse and variable GS (Fig. 2) indicates an alternation of shallow and intermediate lakes at the sampling site during the Late Holocene. However, human impacts on the environment have to be considered because river water was diverted for irrigation during at least the last 2000 years. The alternation of soil and loess at around 3.7 ka at the YX section and 3.5 ka at the JZT section (Fig. 3) indicates humid but variable climate during the Late Holocene. During relatively wet periods, such as 2.4–2.0 and 1.0–0.5 ka, vegetation was similar to that of the Early Holocene (Fig. 4), and the vegetation cover

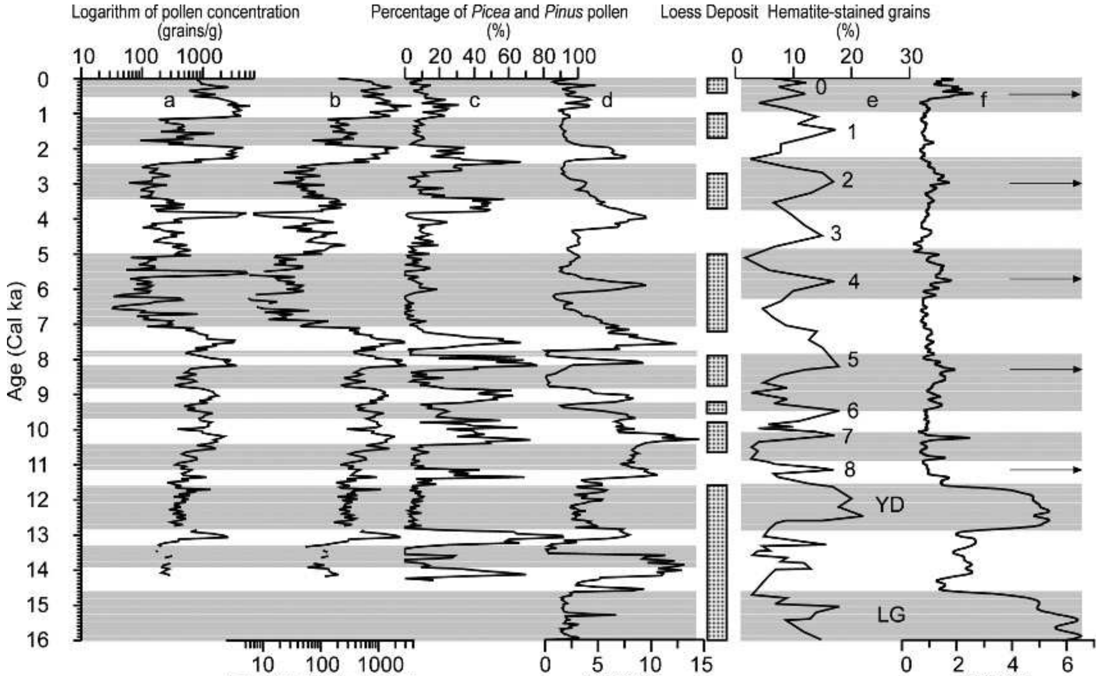

Fig. 6. Total pollen concentrations, high-elevation vegetation pollen concentrations, Picea–Pinus *percentages, $CaCO_3$ contents of the SJC section, and a summarized Holocene loess–soil sequence for the Loess Plateau correlated with percentages of hematite-stained grains in Core VM29-191 in the Northern Atlantic, an ice-raft and temperature proxy record (Bond et al., 2001), and potassium ion content in the GISP2 ice core, a proxy of the Siberian High (Mayewski et al., 2004). The episodes of high hematite-stained grain content following the last glacial are marked in sequence from #0 to 8, YD (Younger Dryas) and LG (last glacial) based on Bond et al. (2001). The black arrows point to the dust flux peaks in the Greenland ice core that are related to continental dry events (O'Brien et al., 1995). Shaded areas indicate periods of weak summer monsoon and, thus, dry climate events in the study area and principal periods of a strong Siberian High.*

increased in both the uplands and lowlands. During dry periods, the vegetation cover was reduced much as during the Middle Holocene, with relatively high *Sabina*, Chenopodiaceae, and *Nitraria* pollen and low LOI content. The lower reaches of the drainage basin apparently became very dry because vegetation was dominated by Chenopodiaceae and *Nitraria.* Around 3.0 ka, the lake was shallow or even dry near the section because charcoal and pottery of this age were found at an archeological site 1 km away. Additionally, glaciers expanded at this time and conditions were generally dry in western China (Zhou *et al*., 1991). The eolian loess layer at the upper part of the Holocene soil at the YX and JZT sections (Fig. 3) is dated to around 3 ka, supporting other evidence of high dust input and dry climate. Huang *et al.* (2002) also reported a regional aridity in the Loess Plateau in this period.

In summary, the records from the lacustrine sediments of the SJC section and from the Holocene loess–soil sections across the Loess Plateau show a generally humid climate following the deglacial until around 7 ka in the northwest margin of the East Asia summer monsoon. This was followed by a dry climate during the Middle Holocene from 7 to 3.8 ka, with a very dry climate between 7 and 5 ka. The climate was highly variable during the Late Holocene.

4.3 Millennial-Climate Viability since the Deglacial

Although the total pollen assemblage from the SJC section reflects long-term vegetation and climate changes, millennial–centennial variations since the last glacial are most obvious in proxies such as *Picea–Pinus* percentages of the montane forest vegetation, pollen concentrations, and carbonate content (Fig. 5). High *Picea–Pinus* percentages, a proxy of a humid climate (Zhu *et al*., 2002), show a distinct periodicity (Fig. 5). Two high *Picea–Pinus* percentage peaks between 14.3 and 12.8 ka document a warm Bφlling–Allerφd period, while the following very low percentages likely document the YD event during the deglacial. LOI and carbonate contents co-vary and are likely proxies for biological productivity. Variations in these proxies are similar to those of *Picea–Pinus* percentages (Fig. 6). During the Early Holocene, 11.6–7.1 ka, periods of high *Picea–Pinus* percentages at 11.6–11.1, 10.4–9.7, 9.3–8.8, 8.2–7.9, and 7.8–7.1 ka (Fig. 6) indicate five humid periods that appear to correspond to episodes of elevated groundwater in the eastern Tengger Desert (Madsen *et al*., 1998; Madsen *et al*., 2003). During these periods, the *Picea* forest apparently expanded in the Qilian Mountains, and *Pinus*, broadleaf trees, shrubs, herbs, and ferns in the forest understory were also better represented. Pollen concentrations are also relatively high during these periods, suggesting generally high vegetation density in the drainage basin. High *Sabina* percentages indicate the climate became relatively dry at 11.1–10.4, 9.7–9.3, 8.8–8.2, and 7.9–7.8 ka. *Picea–Pinus* and broadleaf forest decreased, and the forest zone at high elevations was composed primarily of *Sabina*. Low pollen concentrations suggest that vegetation density was reduced. The relatively low LOI and $CaCO_3$ contents at the section during these periods (Figs. 2 and 6) support an interpretation of a low vegetation cover in the drainage and low lake productivity.

Three *Picea–Pinus* percentage and pollen concentration peaks occur at around 1.2–0.5, 2.4–2.0, and 3.8–3.4 ka, consistent with high $CaCO_3$ and LOI content during the Middle and Late Holocene after 7.1 ka. During these periods, montane *Picea–Pinus* conifer forest apparently expanded along the northern slopes of mountains on the Tibetan Plateau margin, indicating periods of strong summer monsoon. High LOI content reflects periodic high lake productivity. The high amounts of LOI and $CaCO_3$ persisted from 4.3 to 3.4 ka, longer than comparable pollen proxies during the 3.8–3.4 ka humid period. An obvious $CaCO_3$ peak (Fig. 6d) occurred around 6 ka, but *Picea–Pinus* percentages and pollen concentrations did not increase (Figs. 6a–c). The pollen assemblage suggests montane vegetation cover was low during the period, while lake productivity was high. This inconsistency may be the result of variation between the Indian and East Asian summer monsoons. For example, Hong *et al.* (2005) suggested that there was a strong East Asian Monsoon interval around 4 ka with no corresponding strengthening of the Indian Monsoon. The montane forest in the Qilian Mountains, just north of Qinghai Lake on the Tibetan Plateau margin, is extensively affected by the Indian Monsoon (i.e., Wei and Gasse, 1999), possibly explaining the inconsistency.

This study shows that the climate in the study area had persistent millennial–centennial variability since the deglacial, with centennial-scale and longer variations in the Early Holocene. Spectral analysis of $CaCO_3$, pollen concentrations, and *Picea–Pinus* percentages shows distinct ~1500- and ~500 to 700-year periodicity (Jin *et al*., 2004). The periodicity changes from ~2500-year in the Early Holocene to ~1400-year in the Late Holocene, but the average periodicity is very close to the 1500-year periodicity recorded elsewhere (Bond *et al*., 1997; Bianchi *et al*., 1999; DeMenocal *et al*., 2000), indicating millennial monsoon variation was controlled by internal oscillation of the global climate system after the deglacial (Arz *et al*., 2001).

4.4 Drought Events during the Holocene

In the SJC section, relatively low pollen concentrations, low percentages of *Picea–Pinus* pollen, and low $CaCO_3$ (also LOI) content indicate a dry climate during weak summer monsoon periods. There are 10 dry climatic episodes dating to 0–0.5, 1.2–1.9, 2.4–3.4, 5.0–7.1, ca. 7.9, 8.2–8.8, 9.3–9.7, 10.4–11.1, 11.4–12.8 and 13.3–13.8 ka (Fig. 6). The very high pollen concentration peaks around 5.5 ka (Fig. 4) are probably the result of local factors, as the pollen assemblage is dominated by xerophytes such as Compositae and *Nitraria.* The $CaCO_3$ peak at around 6 ka may indicate a humid interval within the long dry period from 7 to 5 ka, during which most lakes in the Alashan Plateau (part of the southern Mongolian Plateau) were totally dry or reduced to shallow levels (Chen *et al*., 2003).

In the Holocene loess–soil sequence of the Loess Plateau, not all sections document all the dry events, something that is to be expected because of differential soil erosion and differential local precipitation. However, they do record high dust input and interruptions of Holocene soil development (Fig. 3). To summarize all of the layers of Holocene loess and relatively weak pedogenesis, the dry events took place around 1.7–1.0 ka (JY, JZT, and YX sections, see Fig. 3), 3.7–2.7 ka (JZT and YX sections), and 7.5–5.0 ka, with a possible humid interval around 6 ka (JY and QS sections). The soil at the GQ section formed during the Early Holocene, but three weak pedogenesis (i.e., loess) layers interrupted soil formation. The most recent of these dates to about 7.9–8.7 ka, with the earliest one dating to 10 ka (Fig. 3). Considering the limitations of OSL dating accuracy, the Holocene loess intervals documented at different sections appear to coincide with dry intervals documented at the SJC lacustrine section. Figure 6 gives the summary of all high dust events recorded in the Loess Plateau during the Holocene. The main problem with Holocene soil records is that it is hard to find a single section that can record all of the short dry intervals due to differential soil erosion both by water and by wind, differential interplay between dust deposition and soil development, and different section locations. For example, although the GQ section is at the northwest margin of the Loess Plateau and close to the sandy deserts, it is situated on a Holocene river terrace and has a thick Early Holocene soil (ca. 5.0 m). High dust deposition and fluvial loess sedimentation make it possible to document three dry climatic events during the Early Holocene that cannot be recognized at the sections such as JY and YX in the southern Loess Plateau. However, if we assemble all the sections, it is easy to identify all the dry events (Fig. 6).

The identified dry episodes correlate well with high percentages of hematite-stained grains in Core VM29-19 that indicate high ice-rafted debris in the Atlantic Ocean and an association with cold climate (Bond *et al.*, 2001; Porter and Zhou, 2006). They also correspond to high points in the GISP2 potassium ion proxy associated with a strong Siberian High (Mayewski *et al.*, 2004). The low pollen concentrations and *Picea–Pinus* percentages at the top of the SJC section over the last 500 years and the loessic-cultivated layer at the YX section may reflect the Little Ice Age, something also evident in peaks in hematite-stained grains in Core VM29-19 and in the GISP2 potassium ion proxy (Fig. 6). The very obvious peak (#4) of hematite-stained grains and GISP2 K^+ content (Fig. 6) correlates with the strong mid-Holocene dry interval recorded in the SJC lake sediments and several Holocene loess sections such as the QS, JY, and GQ sections (Fig. 3). There were five periods of strong Siberian High during the Holocene, as indicated by potassium ion changes (Fig. 6; Mayewski *et al.*, 2004) and by high dust flux recorded in the Greenland ice core (arrows in Fig. 6; O'Brien *et al.*, 1995). Considering the chronological uncertainty of the age model and the resolution differences in the records, the five periods of strong Siberian High and dust flux events coincide remarkably well with the strong dry periods in our pollen record and Holocene loess–soil sections (Fig. 6). Because dust in the Greenland ice comes mainly from arid central Asia, especially the arid lands of northwestern China (Biscaye *et al.*, 1997), and because a strong Siberian High eventually results in a strong winter monsoon and a dry/dusty climate, the five high dust-influx and Siberian High events should also indicate five periods of markedly dry climate in arid and semi-arid China during the Holocene. The hematite-stained grain proxy indicates nine episodes of cold climate during the Holocene (#0–8 beside the hematite-stained grain curve in Fig. 6). Although the #3 event is not well documented in our pollen record and there are slight chronological differences in cold events recorded in the Early Holocene, all of the cold climatic events in the North Atlantic are well represented as dry climate events in the interior continental terminal lake and the dust-deposition areas of the Loess Plateau that we studied.

Although the climatic events documented by the hematite-stained grain proxy from the North Atlantic core, the GISP2 K^+ content, and our own proxies from the SJC section correlate well, it should also be noted that there are obvious differences. The hematite-stained grain cold event peak #1 is not reflected in the GISP2 K^+ Siberian High proxy, while a dry climate is documented in the SJC lake section and at loess sections such as JY, JZT, and YX at that time. The hematite-stained grain peak #3 is recorded neither in the GISP2 K^+ proxy nor in our monsoon margin data. Our pollen assemblage records a longer dry period in the mid-Holocene than either of the GISP2 K^+ or of the hematite-stained grain records. The pollen assemblage at the SJC section documents a humid, but variable, Early Holocene climate with four marked dry episodes (Fig. 6), of which three episodes are well documented in the GQ Holocene soil section (Fig. 3). This sequence is similar to the hematite-stained grain proxy, but different from the GISP2 K^+ proxy. At most loess sections in the Loess Plateau, only one paleosol layer developed as part of the Early Holocene S0 paleosol complex (Porter, 1991; Zhou *et al.*, 1991). However, at most northern monsoon margin sites, such as the GQ section, three loess layers were found to be very common on low terraces during our fieldwork (see also Porter and Zhou, 2006). These may correspond to relatively high GISP K^+ peaks and high percentages of hematite-stained grains. The YD event at the SJC section is associated with low pollen concentrations, very low *Picea–Pinus* percentages, and low carbonate content (Fig. 6). A similar short, dry climate event is also documented around 13.5 ka during the Bφlling–Allerφd interstadial at the SJC section. These two dry events may well be correlated with two high percentage peaks of the hematite-stained grains. The differences among the records may indicate complex responses of the East Asian Monsoon, the Siberian–Mongolian High, and ice-drift intensity in the North Atlantic to temperature changes possibly induced by solar variations (Bond *et al.*, 2001). The different time resolutions and chronological accuracies of the geological records may also make detailed correlation difficult. Although differences exist among the records, the climatic changes evident in high-latitude Atlantic records and in Eurasian continental interior records are more similar than different. Therefore, our pollen data from the SJC lake section and from soil records in the Loess Plateau support at least hemispheric, if not global, climatic event correlations at multi-centennial to millennial time scales during the Holocene.

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Vegetation evolution in arid China during Marine Isotope Stages 3 and 2 (∼65–11 ka)

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Abstract

The three characteristic areas of western China – the Tibetan Plateau, the Loess Plateau and the lowland desert areas – show a vegetation evolution of strong temporal and spatial variability during the Marine Isotope Stages (MIS) 3 and 2. Most of these vegetation changes can be related to regional climate variability recorded in various climate archives.

Most areas of western China are covered by steppes and forest steppes during the MIS 3. The optimal climate conditions for vegetation growth (warm and wet) occurred at the later MIS 3 around 40 ka causing the expansion of forests on the Tibetan Plateau and the Loess Plateau beyond their present-day limits. Due to the generally dry and cold climate around the time of the Last Glacial Maximum (LGM) (∼21 ka), western China was mostly covered by deserts and semi-deserts during this period. The late glacial vegetation is characterized by several changes on millennial time scale: the vegetation optimum during the Bølling/Allerød period (∼15–13 ka) yielded a large-scale forest expansion, a deterioration of the vegetation condition occurred during the Younger Dryas event around 12 ka. The transition towards a warmer and wetter climate at the beginning of the Holocene is evidently indicated in most vegetation records showing especially the spreading of broad-leaved trees on the Loess Plateau and at the margins of the Tibetan Plateau.

1. Introduction

Although the arid regions in western China comprise a huge land area – including the greater parts of the Tibetan Plateau, the Loess Plateau and the lowlands of the Tarim Basin, the Junggar Basin, the Alashan Plateau and the Ordos Plateau (Fig. 1) – no review on vegetation evolution during MIS 3 and 2 exists. This information is especially important when attempting to determine human colonization of these lands. Although we do possess basic information on climate change in the area (see the other papers in Section II and Herzschuh, 2006), it is the landscape features of vegetation and access to open water that, as Madsen *et al.* (this volume) note in the introduction, are most responsible for changes in the human use of these areas. Physical and climatic parameters like precipitation and temperature change are rather secondary. This chapter is an answer to the need to address these primary-determining factors.

Vegetation composition and water availability are, of course, mainly a function of climate. Since the Late Holocene period, however, human impact has played an increasingly prominent role in climatic change. As a result, the distribution of the principle present-day vegetation types generally not only reflects the climatic conditions in the area, but also includes significant human influences. This human influence is especially true for the comparatively wet (> 500 mm precipitation), formerly forested, areas along the eastern margin of the Tibetan Plateau (originally mainly coniferous forests) and the southern and central part of the Loess Plateau (originally mainly deciduous and mixed forest) that are now widely used for agriculture and intensive herding. In relatively warm semi-arid areas (> 8° C of July temperature; 400–200 mm annual precipitation) like the northern Loess Plateau and the Qinghai Lake area, temperate steppes are preserved, while the colder areas of north-eastern and central Tibetan Plateau are covered by alpine steppes. However, both steppe types are dominated by *Stipa* and *Artemisia*. Temperate semi-deserts and deserts (mostly dwarf-shrubs, e.g. Chenopodiaceae, Tamaricaceae, *Nitraria*, *Calligonum*) dominate the warm and dry lowlands of the Ordos Plateau, the Alashan Plateau, the Junggar Basin and the Tarim Basin. More detailed information on vegetation types and their distribution in western China can be derived from the "Vegetation Atlas of China" (Wu, 2001).

What are the reasons for the lack of overview of palaeo-vegetation information? Generally, the scarcity of published vegetation records can be attributed to the difficulty in accessing most areas of arid China and by the limitations of available archives. Furthermore, some palaeo-vegetation records are published only in the Chinese language and are therefore not accessible to the international scientific community. With this review on vegetation change during MIS 3 and 2 in arid China, we aim to bring together the scattered information available and use it to help address the specific aims of this volume.

2. Palaeo-Vegetation Records Available and Their Limitations

The three regions composing arid western China – the Loess Plateau, the Tibetan Plateau and the lowland basins – differ

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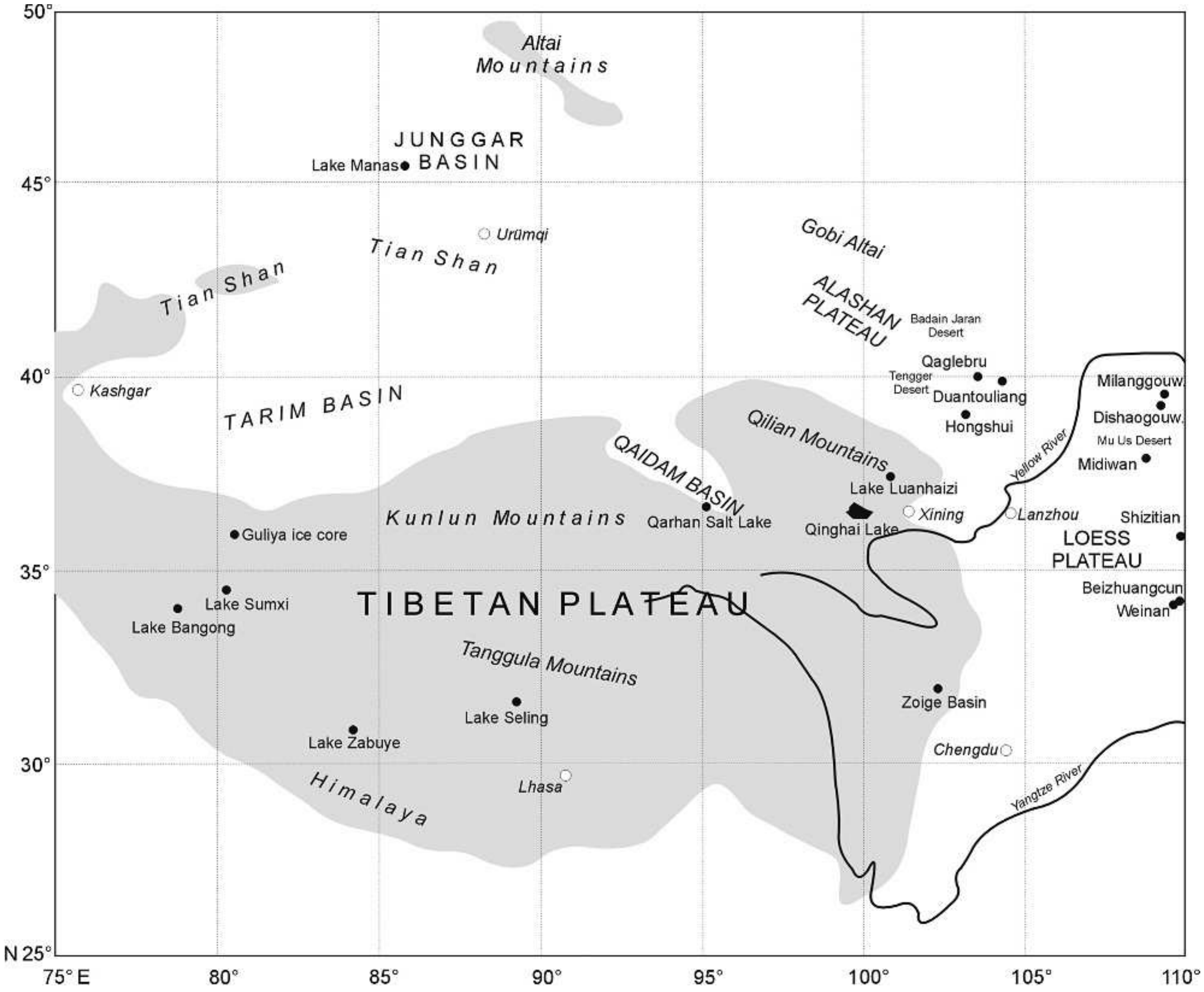

Fig. 1. Overview on western China. Black dots mark the location on the vegetation records mentioned in the text.

not only in the dominant vegetation types and climate conditions, but also in the kind of palaeo-vegetation archives available. While loess sequences are the most important palaeo-vegetation archives on the Loess Plateau, lake sediments from the Tibetan Plateau and its northern forelands can be analysed palynologically. Because the sedimentation process in many large and deep lakes was not interrupted during the glacial period, there is great potential for deriving long-term records from the Tibetan Plateau. To date, however, there exist only very few pollen records from this area. Archive availability is generally less promising in the large lowland areas north of the Tibetan Plateau (Ordos Plateau, Alashan Plateau, Junggar Basin, Tarim Basin), although there are several large lakes. However, most of these shallow closed-basin lakes changed their location or dried up several times during the last 65 ka and continuous records are not available from these regions. Furthermore, these lakes are fed by mountainous rivers containing a high mountain pollen load (Zhu *et al*., 2002a; Zhu *et al*., 2002b; Zhu *et al*., 2003) which blurs the lowland vegetation signal in the pollen records.

The dating of MIS3/MIS2 archives is the crucial point determining their scientific value. Although less precise than for the Holocene period, radiocarbon dating is still the most frequent method applied for dating late MIS3 and MIS2 lake sediments. The reliability is even more reduced when dating sediments from closed-basin and hard-water lakes – which most of the large Tibetan lakes are – since they often show a significant reservoir effect. Besides the radiocarbon method, U/Th and luminescence dating are also applied to loess sequences. Due to these dating uncertainties, we compared vegetation changes from different sites only on a rather broad time scale and omitted the correlation of sub-millennial variability.

Several comparatively new methods, such as *n*-alkane analysis and carbon stable isotope analysis of loess sediments (Liu *et al*., 1996; Xie *et al*., 2002), have been applied in arid China to infer palaeo-vegetation. Pollen analysis, however, is still the most important method for the reconstruction of terrestrial vegetation, since only few macrofossil records exist from the area (Herzschuh *et al*., 2005), possibly due to the scarcity of suitable peaty sediments. Pollen records generally provide a large amount of information pertinent to the dating process. To compare general trends between different regions, some data reduction methods have been applied to raw pollen data. These are primarily the establishment of pollen ratios such as the arboreal/non-arboreal pollen ratio for the differentiation between forest and non-forest vegetation, the *Artemisia*/Chenopodiaceae ratio for the differentiation between steppe and desert vegetation (El-Moslimany, 1990) and the *Ephedra fragilis*-type s.l./ *Ephedra distachya* type for the differentiation of warm and cold deserts (Herzschuh *et al.*, 2004).

A quantitative reconstruction of higher-ranked vegetation types like biomes or mountainous vegetation belts can be obtained by the calculation of the affinity of fossil pollen spectra to the different vegetation types (Prentice *et al.*, 1996). This method is based on the objective assignment of pollen taxa to higher-ranked vegetation types (according to their modern ecology and biogeography) resulting in a vegetation type × pollen taxon matrix. A high affinity of a fossil pollen spectrum to a single vegetation type indicates its high spatial distribution during the accumulation of the fossil pollen assemblage. Here, two quantitative vegetation type reconstructions from the north-eastern Tibetan Plateau will be shown (for more details on the method see Prentice *et al.*, 1996).

3. Vegetation Evolution

3.1 MIS 3 to Early MIS 2 (65–25 Ka)[1]

The climate of the last interstadial (MIS 3) in arid China was generally warmer and wetter than before (MIS 4) and after (MIS 2), but it is still under discussion whether or not the climate conditions during optimal phases reached or even exceeded the Holocene level (Thompson *et al.*, 1997; Fang *et al.*, 1999; Herzschuh, 2006 Wünnemann *et al.*, this volume). The continuous Guliya ice core and other palaeoclimatic records indicate that the second half of the MIS 3 was slightly warmer and wetter than the period before, probably even exceeding the present-day conditions (Thompson *et al.*, 1990; Thompson *et al.*, 1997; Shi *et al.*, 2001). This is in accordance with the exceptional strong insolation during this period (Berger and Loutre, 1991). The rapidly increasing number of palaeo-climatic records for the second half of the MIS 3 gleaned from lake sediments also testifies a two-step climate amelioration after the end of the MIS 4.

The transition from the MIS 4 to the MIS 3 around 65 ka is reflected in the Weinan pollen profile from the southern Loess Plateau by a strong increase in tree pollen percentages, indicating the establishment of broad-leaved deciduous forest patches (mainly *Ulmus*, *Betula* and *Corylus*) in a meadow–steppe environment formerly covered by dry steppes in which *Artemisia*, Poaceae and Chenopodiaceae dominated (Sun *et al*, 1997). Furthermore, *Picea* patches occurred even in the basins of the south-eastern Mu Us Desert adjacent to the northern Loess Plateau, as indicated by the Dishougouwen pollen record (Sun *et al.*, 1997), and at the nearby Milanggouwan section a significant amount of broad-leaved tree pollen were recorded (Sun *et al.*, 1991; Li *et al.*, 2000). The main part of the Loess Plateau, however, was covered by steppes dominated by *Artemisia* throughout the MIS 3 and there are no consistent indications for differences between an early and late phase of the MIS 3 on the Loess Plateau (Jiang and Ding, 2005).

We have almost no reliable information on the vegetation evolution during the MIS 3 in the large basins of arid China. A poorly dated record (Qaglebru section) from the southern fringe of the Badain Jaran Desert revealed desert conditions dominated by Chenopodiaceae and *Artemisia* during the first half of the MIS 3 (until ~43 ka BP) and a slight improvement in the growing conditions during the second half (Dong *et al.*, 1996). The Duantouliang section from the Tengger Desert (Ma *et al.*, 1998; Zhang *et al.*, 2002) at the northern foreland of the Qilian Mountains might be influenced by fluvial deposition, erosional processes and re-deposition, and its pollen record tend to reflect the depositional conditions and pollen transportation from the mountains, rather than lowland vegetation change (see modern pollen deposition studies by Zhu *et al.*, 2003). Some general features on regional vegetation change might nonetheless be inferred: the vegetation between 42 and 38 ka BP is characterized by high values of arboreal taxa and Chenopodiaceae indicating the spreading of forests in the mountains between and the dominance of desert vegetation in the lowlands. The MIS 3 vegetation conditions of the Junggar Basin were depicted by the lowermost samples (~35 ka) of the Manas Lake pollen record (Rhodes *et al.*, 1996), which shows *Artemisia*/Chenopodiaceae ratios of less than 1 – indicating the occurrence of desert vegetation (Cour *et al.*, 1999; Herzschuh *et al.*, 2004) during this period.

Palaeo-vegetation records from the Tibetan Plateau going back to the MIS 3 are rare. Pollen analyses of the first 60 m of core RM from the Zoige Basin provide continuous information on the last 200 ka (Shen *et al.*, 2005) indicating strong changes in the vegetation cover. The last two interglacials (MIS 5e and Holocene) were characterized by coniferous forests indicated by arboreal pollen content above 50%, while the last glacial is characterized by strong oscillations between dense coniferous forests (high arboreal pollen content), alpine steppes and deserts (high values for *Artemisia*, Chenopodiaceae, and non-*Artemisia*, Asteraceae, Poaceae) and alpine meadows (high values for Cyperaceae) which have been correlated with Dansgaard–Oeschger-events recorded in Greenland ice cores. The first half of MIS 3 was mostly dominated by alpine meadows. Maximum arboreal pollen content within MIS 3/2 occurred between 43 and 39 ka BP consisting of *Picea*, *Pinus*, Abies, *Betula* and *Quercus*.

Several records indicate an extension of forests several hundred kilometres beyond their present-day limits on the Tibetan Plateau during this time. Pollen analyses of Zabuye Lake sediments in central Tibet yielded pollen assemblages

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[1] All ages are in calendar years unless otherwise noted.

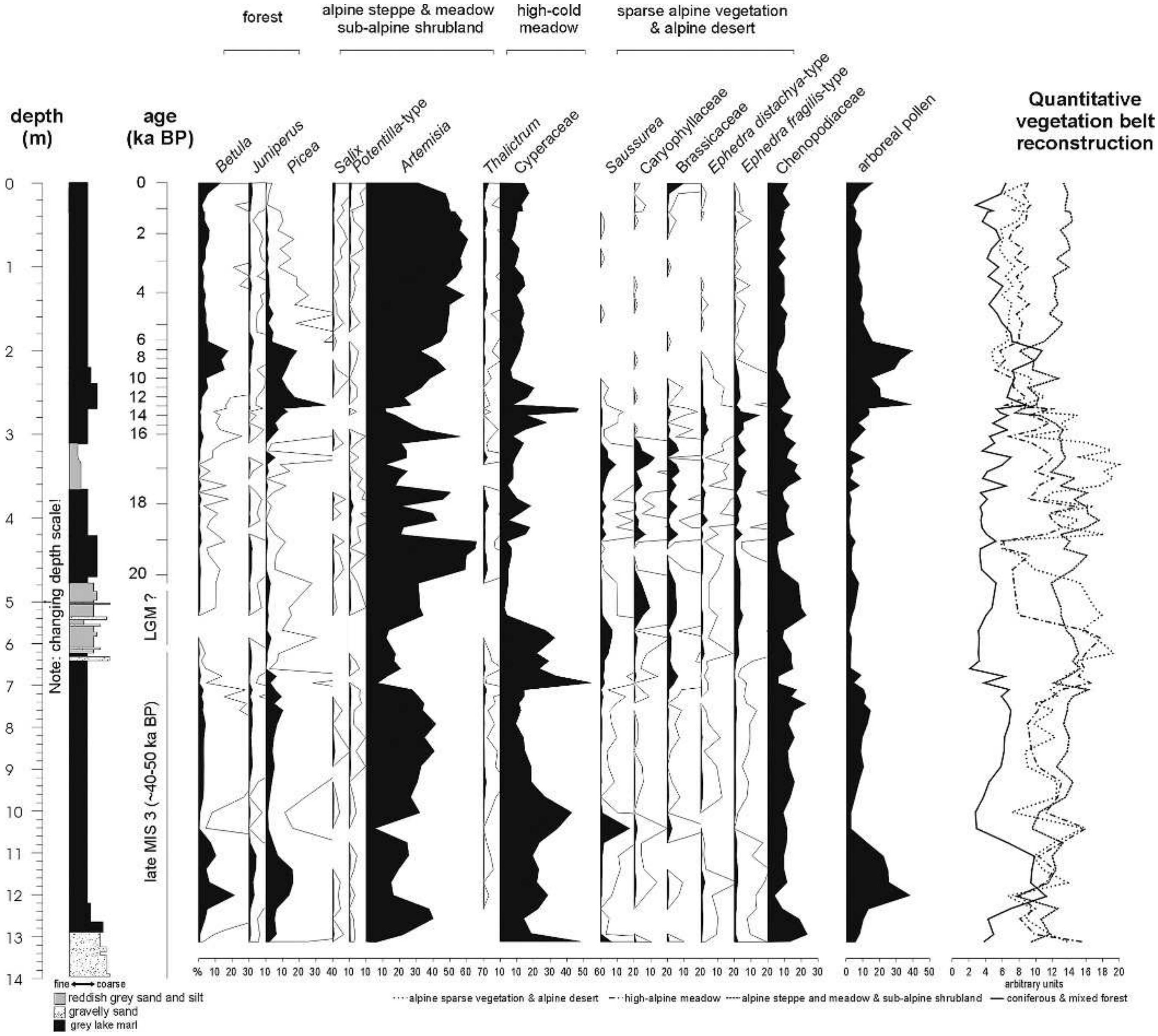

Fig. 2. Pollen record of Lake Luanhaizi from the Qilian Mountains and a reconstruction of the dominant vegetation type changes (from Herzschuh et al., 2006, slightly changed).

which are dominated by *Pinus*, *Picea* and *Abies* (Xiao *et al.*, 1996) and thereby reflect the occurrence of coniferous forest in an area which is today covered by high-alpine dry steppe. Similar results regarding the spreading of tree taxa on the Tibetan Plateau are also reported from the Bangong Lake area between 36 and 28 ka in western Tibet (mostly *Larix*, *Pinus*, *Betula*; Huang *et al.*, 1989; quoted from Shi *et al.*, 2001) and from the Qinghai Lake area between 39 and 26 ka (mostly *Picea*, *Pinus*, *Abies*; Shan *et al.*, 1993, quoted from Shi *et al.*, 2001). These findings from localities across the Tibetan Plateau match the simultaneous occurrence of *Picea* forests above the present-day timberline at the margin of the eastern and north-eastern Tibetan Plateau very well. Patches of coniferous forests became common in the Qilian Mountains (Fig. 2, Herzschuh *et al.*, 2006) and in the Zoige Basin (Shen *et al.*, 1996; Shen *et al.*, 2005), which were again replaced by alpine steppes, meadows and deserts at the end of the MIS 3.

The transition from the MIS 3 climate to the climate around the LGM (∼30–21 ka) is characterized by an overall decreasing moisture trend in central Asia (Herzschuh, 2006; Wünnemann *et al.*, this volume). The Guliya ice core record, however, indicates very strong climate variability on a centennial time scale (Thompson *et al.*, 1997), which is possibly the reason why available low-resolution vegetation records of this period do not show a clear trend. The vegetation in the Zoige Basin (Wasong section; Yan *et al.*, 1999) changed from alpine desert to alpine meadow, and the central Tibetan Plateau vegetation varied between moist shrub steppe and dry alpine steppe (Wu and Xiao, 1996). The pollen records from the Loess Plateau suggest likewise strong spatial and temporal variability during this period. The vegetation around the Weinan Loess profile (a plateau area of southern Loess Plateau) changed from dry steppe (34–25 ka) to *Corylus* dominated woodland (25–21 ka). It later switched to a high-alpine meadow type dominated by different Asteraceae (21–13.7 ka). A nearby river valley (Beizhuangcun pollen profile), in contrast, was covered by *Picea* forest steppe at least twice (31–28 ka and 24–23 ka). Most of the Loess Plateau was still covered by *Artemisia*-rich steppes (Jiang and Ding, 2005) or *Artemisia*–Chenopodiaceae-rich desert steppes (e.g. Shizitian section, central Loess Plateau; Xia *et al.*, 2002), however. The vegetation on the southern fringe of the present-day Mu Us Desert (adjacent to the northern Loess Plateau) oscillates between semi-arid steppe and humid forest steppe on millennial time scale (Li *et al.*, 2000). Further lowland sites in western China also exhibit similarly strong vegetation variability (e.g. Tengger Desert: Duantouliang section, Zhang *et al.*, 2002; Hongshui river section, Ma *et al.*, 2003).

3.2 Around the LGM (∼21 Ka)

Generally, a strongly intensified winter monsoon and a weakened summer monsoon characterize the climate around the LGM (∼21–19 ka, e.g. An *et al.*, 1991; Chen *et al.*, 1997; Wang *et al.*, 1999). Accordingly, most palaeoclimate records from the area yield dry or moderate dry conditions (Herzschuh, 2006). However, some scientists suggest that higher effective moisture during this period in western China was due to less evaporation at lower temperatures and stronger influence of the westerlies (Qin and Yu, 1998; Shi, 2002; Yu *et al.*, 2003).

The biome reconstruction for 18 ^{14}C ka (LGM) presented by Yu *et al.* (2000) suggests steppe and desert biomes extended southwards to 30° N into the lowlands of present-day China and to the present-day eastern coast. Although it is represented only by a few sites, vegetation reconstruction for the Tibetan Plateau displays mostly desert conditions. This vegetation reconstruction is consistent with the Luanhaizi pollen record from the Qilan Mountains (Fig. 2; Herzschuh *et al*, 2006) which shows high frequencies of pollen taxa typical for alpine sparse and alpine desert vegetation (like Caryophyllaceae, Chenopodiaceae, *Ephedra* and several non-*Artemisia* Asteraceae pollen types, e.g. *Saussurea*) suggesting both dry and cold climate conditions. Similar high-alpine desert vegetation with exceptional high Asteraceae pollen percentages was reported from the Loess Plateau (Sun and Song, 1996; Sun *et al.*, 1997; Jiang and Ding, 2005) and the Zoige Basin (core RM; Shen *et al.*, 1996). The glacial flora of the Qaidam Basin is characterized by high *Ephedra* pollen percentages as indicated by the Qarhan Salt Lake pollen record (Du and Kong, 1983). The pollen spectra from the Hongshui River section I in the Tengger Desert indicates a decrease of *Picea* and an increase of Cyperaceae, *Artemisia* and Chenopodiaceae indicating the establishment of alpine meadows on former *Picea* stands in the Qilian Mountains and the establishment of desertic steppes in the lowland areas (Ma *et al.*, 2003). The period of the LGM was possibly characterized by strong oscillations of climate and vegetation cover (Xue and Zhou, 2000).

3.3 Late Glacial Period to the Beginning of the Holocene Period (19–11 Ka)

After the LGM, records indicate the advent of a phase of slightly wetter conditions in continental Asia – between ∼19 and 17 ka (Herzschuh, 2006 and references cited there) – which possibly represents the onset of summer monsoon circulation. The vegetation belt reconstruction of the Lake Luanhaizi pollen record from the Qilian Mountains (Herzschuh *et al.*, 2006) indicates the establishment of steppe vegetation intermixed with high-alpine deserts. Generally, the vegetation cover shows a strong instability during this period, especially around 18 ka, which is also evident from the lowermost samples of the Qinghai Lake pollen record (Fig. 3; Shen *et al.*, 2005).

Around 16 ka, the climate became slightly drier in the region (Chen *et al.*, 1997; Herzschuh, 2006), which roughly matches a cooling phase recorded in the GRIP ice core record and the Heinrich 1 event in the North Atlantic (Bond *et al.*, 1992). The vegetation cover in the Qilian Mountains decreased and a high-alpine desert such as the one recorded during the LGM became established (Fig. 2). The vegetation around Qinghai Lake (Shen *et al.*, 2005) is likewise characterized by high values for desertic elements like *Ephedra*, although steppes dominated in the area during this time. Comparatively high coniferous values in these samples coincide with very low pollen concentration which indicates a high percentage of pollen grains transported from far away. This is an indicator of low vegetation coverage, not of a regional increase in forest cover.

Many records from monsoonal central Asia demonstrate that the first strong intensification of the Asian monsoon circulation after the LGM took place at the beginning of the Bølling/Allerød period (Zhou *et al.*, 1999; Wang *et al.*, 2001). During this time, the first expansion of coniferous forest vegetation in the Qilian Mountains and the Zoige Basin occurred (Shen *et al.*, 1996; Yan *et al.*, 1999). Steppes and meadows were still the main vegetation types there, however.

This early monsoon enhancement did not significantly improve the vegetation condition on the western and central Tibetan Plateau (Lake Sumxi pollen record, Van Campo and Gasse, 1993; Lake Seling pollen record, Sun *et al.*, 1993) since desert conditions dominated there until the end of the late glacial period. The Younger Dryas event (∼12.8–11.5 ka), reflected as a cold event in Greenland, yielded cooler and drier climate conditions in Central Asia

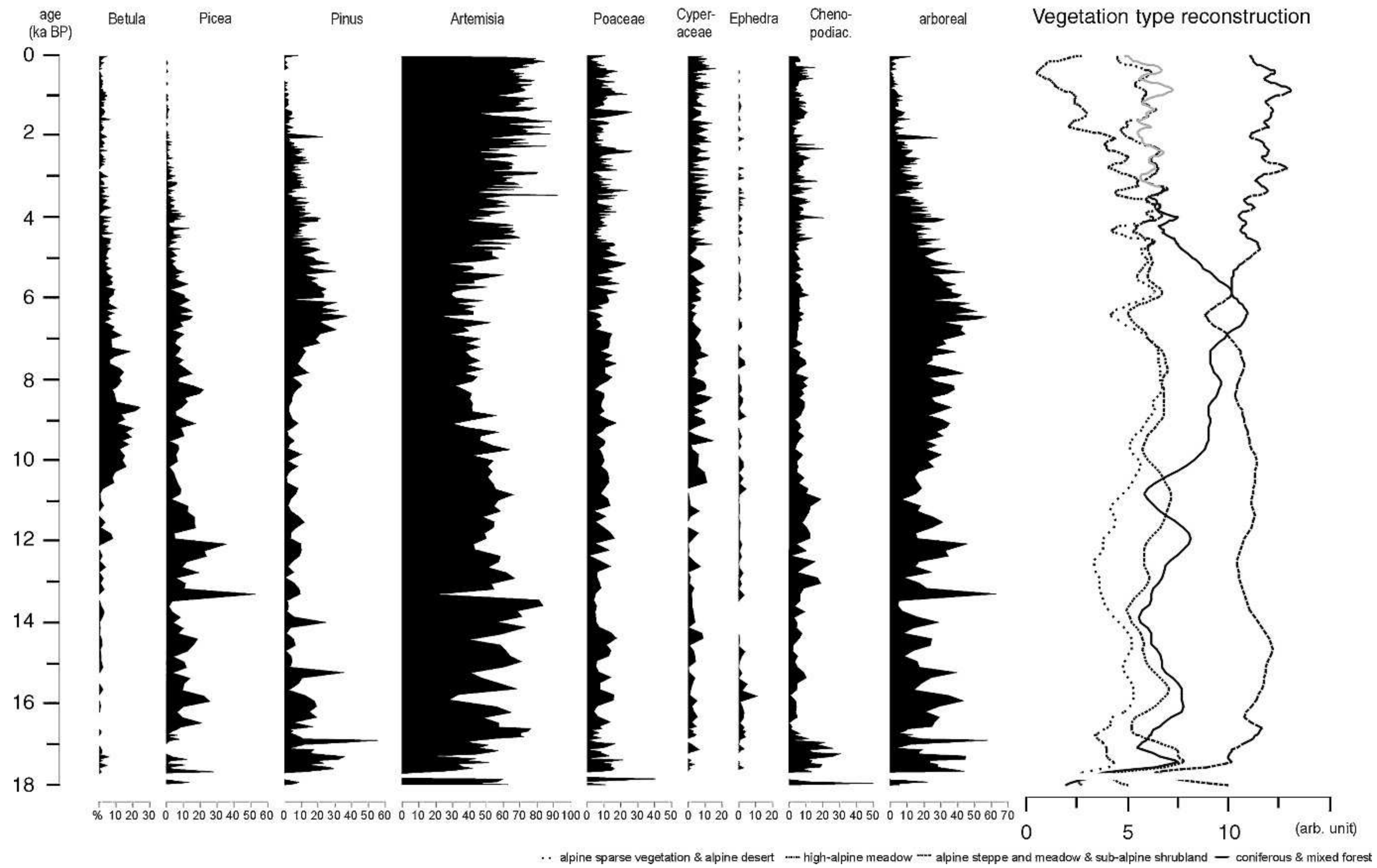

Fig. 3. Pollen record of Lake Qinghai (original pollen data in Shen et al., 2005) and a reconstruction of the main vegetation type changes.

(Herzschuh, 2006) particularly evident in records from the Loess Plateau (Chen *et al.*, 1997; Madsen *et al.*, 1998). It yielded a strong decrease of tree pollen percentage in the Midiwan section at the northern edge of the Loess Plateau (Zhou *et al.*, 1996). There are only few signs of significant vegetation change during this period in other regions (e.g. increase in Chenopodiaceae and *Ephedra* around 11 ka in the Qinghai Lake pollen record; see Fig. 3, Shen *et al.*, 2005) possibly due to the insufficient time resolution of most records. Records from the Tengger desert indicate strong variability in the pollen composition: high amount of *Picea* pollen was recorded at the end of the Younger Dryas, possibly pointing towards an expansion of coniferous trees in the Qilian Mountains, followed by a dominance of *Artemisia*, Chenopodiaceae and Poaceae immediately after the Pleistocene/Holocene transition (Zhu *et al.*, 2002a; Ma *et al.*, 2003).

In contrast to the difficulty involved in compiling a consistent climatic record of the time before, the transition to the Holocene around 11 ka is clearly visible in almost all pollen records available (see also Sun *et al.*, 1991). Records from the Loess Plateau and the north-eastern margin of the Tibetan Plateau show a significant increase in deciduous tree pollen percentages, especially *Betula* (Fig. 2). It is possible, however, that forests did not become established there until ~9000 years ago, while coniferous forest (mainly *Abies* and *Picea*) began dominating the Zoige Basin immediately after the beginning of the Holocene (Shen *et al.*, 1996; Yan *et al.*, 1999). The vegetation on the western Tibetan Plateau switched from desert to steppe as indicated by a strong increase in the *Artemisia*/Chenopodiaceae ratio at Lake Sumxi (Van Campo and Gasse, 1993), Lake Bangong (Van Campo *et al.*, 1996) and Lake Seling (Sun *et al.*, 1993).

While vegetation information on the MIS 3/2 of western China is generally scarce, the number of vegetation records and its data quality (concerning sample resolution and age–model reliability) strongly increase after the beginning of the Holocene (Zhao *et al.*, this volume). Since the vegetation changes were very strong during MIS 3/2 in comparison to Holocene variability they have, nevertheless, been detected in the records.

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Holocene vegetation and climate changes from fossil pollen records in arid and semi-arid China

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Abstract

Holocene variability of the summer monsoons has been documented in a variety of proxy records in east and southwest China. However, its influence on regional climate in other parts of China is still poorly understood, especially further inland in north China and northwest China. Here we review fossil pollen records available from arid and semi-arid areas of China (including Inner Mongolia, the northwestern Loess Plateau, the northern Tibetan Plateau, and Xinjiang) to document regional patterns of Holocene vegetation and climate change, and to understand the large-scale controls of these changes. Pollen records from the four regions reveal different vegetation and wet–dry changes during the Holocene. With the exception of the westernmost sites, vegetation at most sites in Inner Mongolia switches between forest, forest steppe, and typical steppe. There is a dry climate after ~6 ka following early to Early – Mid Holocene maximum moisture conditions. At western sites, the climate was dry in the Early Holocene, wet in the Middle Holocene and dry again in the Late Holocene. Vegetation in the northwestern Loess Plateau switches between desert steppe, steppe, and steppe forest, with corridor forests often occurring in loess valleys during the steppe forest period. These changes indicate wet–dry oscillations, from an initial dry climate to a wet Middle Holocene and then back to a dry climate in the Late Holocene. In the northern Tibetan Plateau, vegetation is characterized by steppe, desert steppe, or desert. However, the Qinghai Lake area was dominated by tree pollen during the Early- and Mid-Holocene, indicating a wet climate, until a drying trend started after 6–4.5 ka. In Xinjiang, pollen assemblages show changes between desert, desert steppe or steppe during the Holocene, with a wet period occurring briefly during the early Mid-Holocene at most sites. The highest moisture interval during the Holocene (the so-called Holocene climate optimum) occurred in the Early- to Mid-Holocene in eastern Inner Mongolia, but apparently occurred later during the Mid-Holocene at sites in the west (northern Tibetan Plateau and Xinjiang). The complex climate patterns during the Holocene in arid and semi-arid China suggest regional climate responses to large-scale climate forcing was controlled by interactions of competing factors including the monsoons, westerlies and topography. The decline of forest in the eastern Tibetan Plateau, the Loess Plateau valleys and Inner Mongolia during the Late Holocene may have been caused by human activity.

1. Introduction

The Asian summer monsoons (Indian and East Asian monsoons) are the most powerful climate systems driving climate changes in the southeastern part of the Eurasian continent at various timescales. During the Holocene, the monsoon intensity followed the summer insolation trend of the Northern Hemisphere, with the maximum monsoon occurring in the Early Holocene and decreasing afterwards (Kutzbach, 1981; Kutzbach and Guetter, 1986). This trend, together with the variability of summer monsoons, has been documented in various proxy records, mostly in east and southwest China (e.g., An *et al.*, 2000; He *et al.*, 2004; Wang *et al.*, 2005), though there are still some inconsistencies. However, its influence on regional climate in other parts of China is still poorly understood, especially further inland in north and northwest China.

Here we review fossil pollen records available from arid and semi-arid areas of China. The region covered in this review includes Inner Mongolia, the northwestern Loess Plateau, the northern Tibetan Plateau (including the northwest part), and Xinjiang. The region is located at the northern limit of influence by both the Indian Monsoon and the Southeast Asian Monsoon, and is also influenced by the prevailing westerlies. The vegetation across this broad region should be sensitive to effective moisture changes during the Holocene due to its location within this area of triangular effects, and to differential responses to these climatic systems (Herzschuh, 2006). Pollen data tend to integrate vegetation signals at a regional scale and have been frequently used in vegetation and climate reconstructions. As a result, fossil pollen has become one of the most widely used paleoclimatic proxies in China and elsewhere. There are, however, few syntheses of pollen data available in dry regions of China (but see Sun *et al.*, 1991; Herzschuh, 2006).

The objectives of this chapter are to review the fossil pollen data from arid and semi-arid regions of China, to document regional patterns of Holocene vegetation and climate changes, and to understand the large-scale controls of these changes. After providing a general background for

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the region, we will explain the criteria that we used to select pollen sites and the data used in this synthesis. We follow with summaries of the vegetation variations in different regions and describe pollen diagrams from representative sites in each region. We then present and discuss patterns of climate variation as interpreted from fossil pollen records across north and northwest China. Finally, we summarize what we learn from this synthetic exercise.

2. Modern Environmental Settings

The geographical region considered in this review covers northern China from 79° E to 118° E longitudes and from 31° N to 49° N latitudes (Fig. 1). The altitude ranges from 194 m to 5325 m above sea level. The East Asian summer monsoon, Indian Monsoon and the westerlies play a significant role in controlling the hydrologic balance and effective moisture of the region. The Indian monsoon extends to the eastern margin of the Tibetan Plateau and to about 40° N, while the southeast Asian summer monsoon brings warm humid air from the Pacific Ocean to the eastern part of our study region. Most of our sites are near the present-day northern limit of monsoonal influences (Fig. 1). North of 40° N latitude, the mid-latitude westerlies prevail and bring relatively dry air from Central Asia to northwest China. The westernmost part of China may receive a small amount of moisture from these westerlies. The transitional area between the monsoon front and the westerly dominance is very sensitive to changes in monsoonal dynamics and interactions between monsoon and westerlies (Li, 1996).

Under the influence of the monsoon systems, annual precipitation decreases sharply from the southeast to the northwest (Fig. 2). Most of our study sites are situated in areas with <400 mm of annual precipitation. In Inner Mongolia and the Loess Plateau, precipitation decreases from southeast to northwest from 400 to <100 mm. On the Tibetan Plateau, the precipitation decreases from >300 mm in the northeast (e.g., at Qinghai Lake) to <50 mm in the northwest (e.g., at Sumxi Lake). In the low-elevation part of Xinjiang, monsoonal air streams rarely reach northern Xinjiang, and the annual precipitation is less than 100 mm. At most of the sites, the precipitation of the three summer months (JJA) usually accounts for 80% or more of the total annual precipitation, leaving winter and spring extremely dry (Ren and Beug, 2002).

The study sites reviewed here are located in one of the three vegetation zones: steppe, desert, and highlands (Fig. 3). A typical temperate steppe occurs in Inner Mongolia and the northwestern Loess Plateau. Its floristic composition mainly includes the families Asteraceae, Poaceae, Chenopodiaceae, and Cyperaceae (Ren and Beug, 2002). These taxa dominate

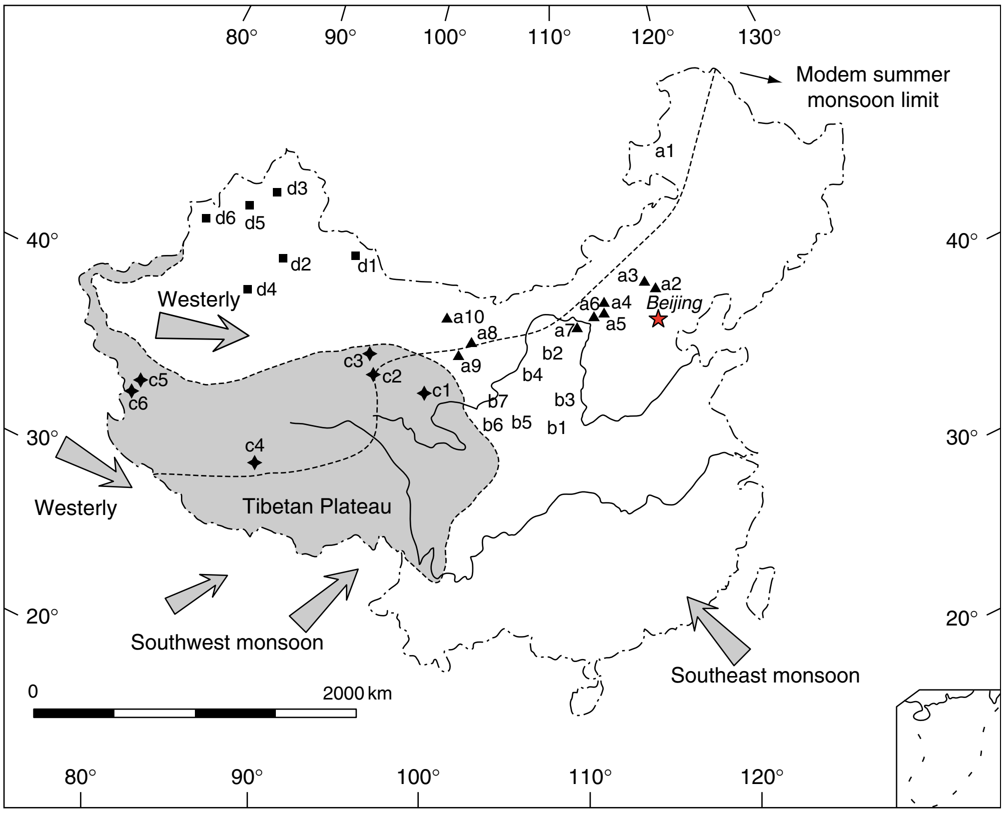

Fig. 1. Map showing the location of fossil pollen sites in north and northwest China reviewed here (see Table 1 for site information and references).

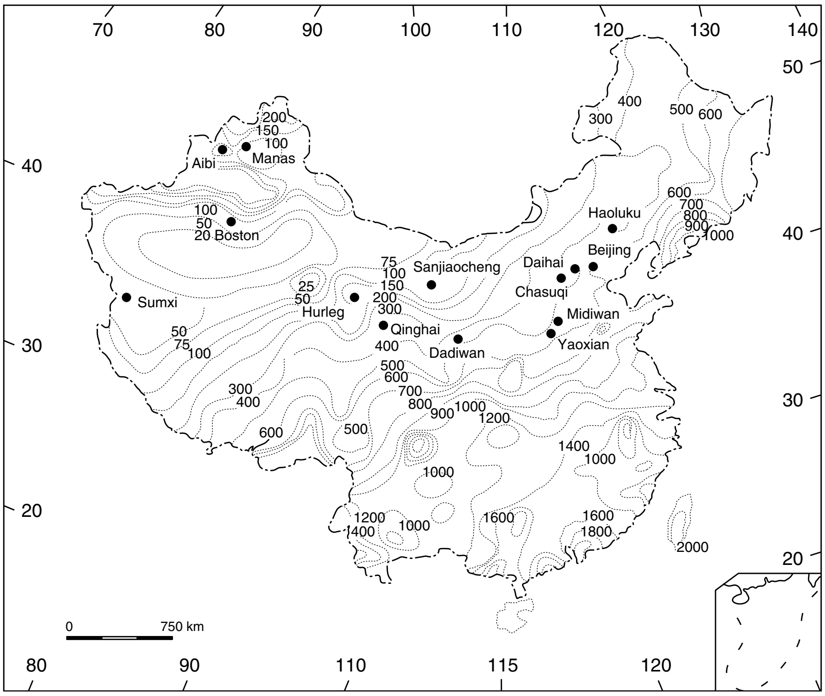

Fig. 2. Mean annual precipitation in China (after Wei and Gasse, 1999).

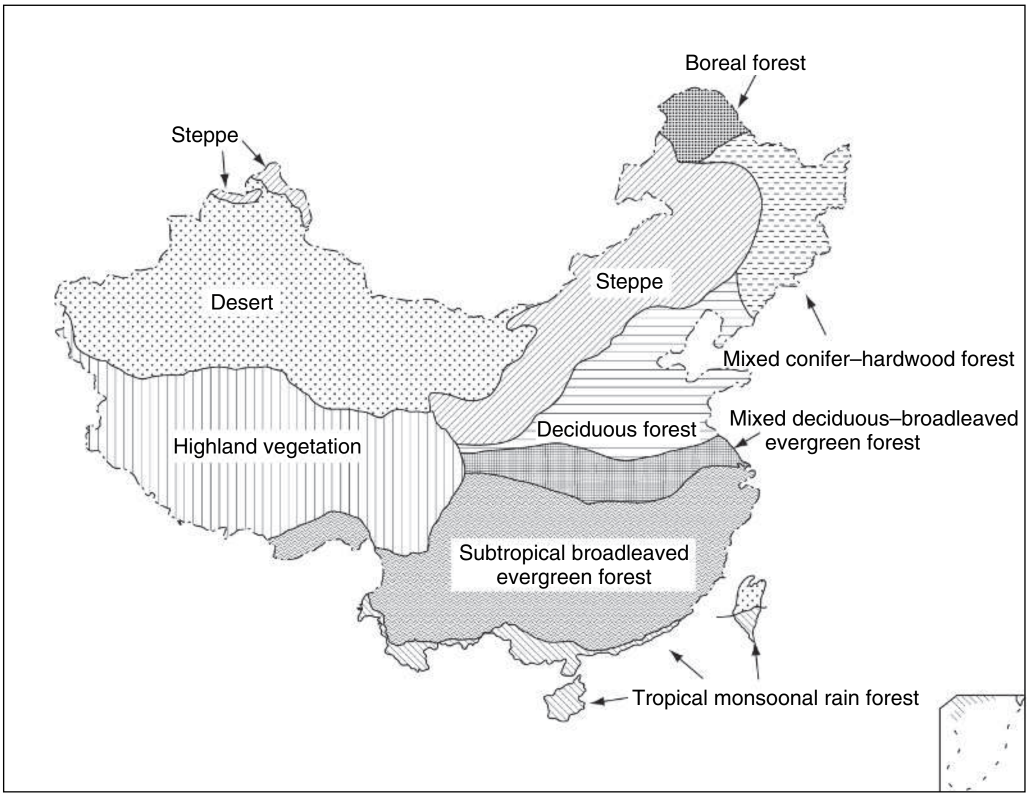

Fig. 3. Dominant biomes (vegetation types) in China (after Wu et al., 1980).

the vegetation in regions where precipitation is 300–500 mm. Temperate deserts are dominated by herbaceous and shrubby plants from the families such as Asteraceae, Poaceae, Fabaceae, Brassicaceae, and Chenopodiaceae. Chenopodiaceae achieve a maximum development in this biome. *Artemisia* abundance can also be high in temperate deserts. In Xinjiang, desert and desert steppe are dominant vegetation types, where precipitation is less than 100 mm. The northern

Tibetan Plateau is mainly covered by alpine steppe and alpine desert, and is dominated by various herbaceous taxa. In the eastern part of the plateau, arboreal taxa are frequently found in mountainous valleys, including *Picea, Abies, Pinus*, *Larix*, *Betula*, and *Quercus*. The alpine steppe is dominated by Poaceae, *Artemisia* and Cyperaceae. The alpine desert is covered by a sparse vegetation, characterized by Chenopodiaceae, *Zygophyllum*, *Artemisia*, Poaceae, *Ephedra*, and *Nitraria*. (Yu *et al.*, 2001). The climate is extremely dry, with an annual precipitation of less than 100 mm and a relative humidity of only 31–33%.

3. Data Sources and Methods

The criteria for site selection include a reliable chronology with a minimum of three dating control points and high sampling resolution with a minimum of 40 pollen samples during the Holocene. We selected 29 fossil pollen sites from the four regions based on our site selection criteria (Table 1). In cases where there are more than one diagram available from a site, we used the one with better dating control and higher pollen sampling resolution.

Radiocarbon dating was the geochronological technique used to date all profiles cited in this chapter, except at Yaoxian (dated by Thermal Luminescence technique) and Dunde ice core (dated by ice layer counting and ice flow modeling). Organic materials or carbonates were used for ^{14}C dating from loess, lacustrine deposits, and peat. We did not attempt to correct old carbon problems at individual sites, if any. In this chapter, all ages for all the reviewed profiles have been calibrated to calendar years before present (BP = AD 1950) using the most recent IntCal04 calibration dataset (Reimer *et al.*, 2004) if they were not calibrated in the original data sets.

We present and discuss six summary pollen diagrams that are representative of vegetation changes in different regions. In arid or semi-arid regions, vegetation is mostly dependent on effective moisture rather than temperature, so in this chapter we mostly focus our discussion on changes in effective moisture. The main pollen indices we use are tree pollen percentage (a moist climate indicator), pollen concentration (a pollen production indicator), *Artemisia*-to-Chenopodiaceae (A/C) ratio (measuring relative dominance of steppe vs. desert pollen), and *Ephedra* and *Nitraria* percentages (as characteristic desert indicators).

It is noteworthy, however, that these pollen indices have some limitations when applied to vegetation and climate reconstruction. The A/C ratio was first introduced by El-Moslimany (1990) in his studies in the Middle East, as an indicator of change in effective moisture in semi-arid and arid regions. This ratio is mostly applicable to vegetation shifts between desert and steppe, which are dominated by plants from Chenopodiaceae and *Artemisia*, respectively. The A/C ratio works well in many regions (e.g., Van Campo *et al.*, 1996; Yu *et al.*, 1998; Cour *et al.*, 1999; Liu *et al.*, 1999; Mischke *et al.*, 2005). However, this ratio may not be applicable if *Artemisia* and Chenopodiaceae are not dominant pollen types in pollen assemblages (if <50% combined). In this case, the A/C ratio may provide misleading interpretations, especially when pollen assemblages have large proportions of tree pollen.

In many studies, total pollen concentrations have been used to indicate climate change, based on the assumption that higher pollen concentrations indicate denser vegetation cover and moist climate (e.g., Liu *et al.* 1998; Chen *et al.* in press). However, this practice may not always be justified. Chenopodiaceae is over-representative in pollen assemblage because of its high pollen production. For example, Herzschuh *et al.* (2003) showed that there was an over-representation of Chenopodiaceae compared to *Artemisia* based on their analysis of surface pollen assemblages from western Inner Mongolia. If that was also the case in the past, then a high pollen concentration may simply represent high abundance of desert Chenopodiaceae plants from a dry desert climate, rather than dense vegetation cover under a moist climate. Also, sedimentation rate plays a major role in determining pollen concentration, as high pollen concentration may be an artifact of slow sedimentation rates. This can lead to major problems with interpretations, especially when sediment cores or sections show dramatic changes in lithology, suggesting major changes in depositional environment and sediment-accumulation rates.

Some desert plants may not be a good vegetation and climate indicator because of their potential for long-distant transport. For example, *Ephedra* tends to travel a very long distance, as its pollen has been documented in midwestern North America, even though its parent plants are thousands of kilometers away in the deserts of the southwestern USA (Maher, 1964). Its low abundance may therefore not indicate the local presence of parent plants and have no climate implications. In addition, some desert plants rely strongly more on groundwater than on atmospheric moisture for growth. For example, *Nitraria* often grows abundantly and well around lakes where the groundwater is close to the surface. Therefore, its local presence may not simply indicate expansion of desert vegetation, but rather a wet climate with increased groundwater levels.

Despite these limitations, we used pollen indices from 29 sites to summarize the dry–wet climate fluctuations during the Holocene. The climatic interpretations, based on changes in effective moisture, are presented along a gradient from the east to west to help document patterns of climate change. As regional vegetation tends to show different responses to large-scale climate changes, we discuss Holocene vegetation changes for each of four regions separately in the next section.

4. Holocene Regional Vegetation Changes

4.1 Inner Mongolia (Including Hexi Corridor)

Ten well-dated pollen records are used for the synthesis in Inner Mongolia (sites a1 – a10; Fig. 1 and Table 1). Daihai Lake (site a5; Xiao *et al.*, 2004) provides a high-resolution

Table 1. *List of fossil pollen sites from arid and semi-arid China used in this review.*

Site No.	Site Name	Province	GPS	Elevation (m)	Dating method	Material dated	Archives	Index	Reference
a1	Hulun Lake	Inner Mongolia	E116°58′ N48°30′40″	no data	C-14	4*	lake section	C/A; pollen concentration	Yang and Wang, 1996
a2	Xiaoniuchang	Inner Mongolia	E116°49.02′ N42°37.05′	1460	C-14	3* bulk sediment	lake section	C/A; AP/NAP	Liu *et al*., 2002
a3	Haoluku	Inner Mongolia	E116°45.42′ N42°57.38′	1295	C-14	4* bulk sediment	lake section	C/A; AP/CAP	Liu *et al*., 2002
a4	Huangqihai	Inner Mongolia	E113°10′ N40°48′	1264	C-14	4*	lake section	pollen percentage; species diversity	Li *et al*., 1992
a5	Daihai	Inner Mongolia	E112°33′ N40°29′	1221	C-14	6*	lake core	total & tree concentration	Li *et al*., 2004
a5	Daihai	Inner Mongolia	E112°33′ N40°29′	1221	C-14	8* organic matter	lake core	tree pollen percentage	Xiao *et al*, 2004
a6	Diaojiao Lake	Inner Mongolia	E112°21′ N41°18′	1800	C-14	4*	lake core	pollen percentage; flux	Shi and Song, 2003
a7	Chasuqi	Inner Mongolia	E116°49.02′ N42°37.05′	1000	C-14	4*	peat section	tree pollen percentage	Wang and Sun, 1997
a8	Sanjiaocheng	Gansu	E103°20′ N39°00′	1325	C-14	13* organic/pollen extract/charcoal	lake bank	pollen concentration; upland tree pollen	Chen *et al*. in press
a9	Hongshui River	Hexi Corridor	E102°45′53″ N38°10′46″	1460	C-14	9* organic matter	river section	pollen assemblage; concentration; A/C	Zhang *et al*., 2000
a10	Eastern Juyanze	Inner Mongolia	E101.85° N41.89°	892	C-14	5* bulk organic material	lake	pollen concentration; A/C; indicator taxa, ca. *Ephedra fragilis*	Herzschuh *et al*., 2004
b1	Fuping	Shan′xi	E 109°50′ N 34°50′	no data	C-14	2*	river section	broad-leaf trees	Sun and Zhao, 1991
b2	Sandaogou	Shan′xi	E109.25° N38.4°	no data	C-14	6*	loess section	pollen percentage	Gao *et al*., 1993

(Continued)

Table 1. (Continued)

Site No.	Site Name	Province	GPS	Elevation (m)	Dating method	Material dated	Archives	Index	Reference
b3	Midiwan	Shan′xi	E108°37′ N37°39′	1400	C-14	23* fossil wood, charcoal, peat	peat section	pollen concentration; total tree pollen	Li *et al.*, 2003b
b4	Yaoxian	Shan′xi	E108°50′ N34°56′	667	TL	2*	loess section	percentage; A/C	Li *et al.*, 2003a
b5	Dadiwan	Gansu	E105°54’53.3″ N35°00′47.3″	1400	C-14	3* charcoal	marsh section	tree pollen percentage	An *et al.*, 2003
b6	Shujiawan	Gansu	E104°31′22″ N35°32′20″	1700	C-14	3* charcoal	marsh section	tree pollen percentage	An *et al.*, 2003
b7	Lanzhou	Gansu	E103°73′ N36°03′	1500	C-14	6* organic matter	loess section	pollen percentage	Wang *et al.*, 1991
c1	Qinghai Lake	Qinghai	E99°36’ N36°32′	3200	C-14	7* TOC	lake core	tree pollen percentage; concentration	Shen *et al.*, 2005
c2	Hurleg Lake	Qinghai	E96°54.126′ N37°18.742′	2809	C-14	7*	lake core	A/C	Zhao *et al.*, 2007
c3	Dunde	Qinghai	E96°24′ N38°06′	5325	Lamination & age model		ice core	pollen concentration; A/C	Liu *et al.*, 1998
c4	Selin Co	Qinghai	E88°31′ N31°34′	4530	C-14	5*	lake core	*Artemisia* percentage	Sun *et al.*, 1993
c5	Sumxi Co	Qinghai	E81°00′ N35°30′	5058	C-14	6* biological material	lake core	A/C	Van Campo *et al.*, 1993
c6	Bangong Lake	Qinghai	E79°00′ N33°40′	4241	C-14 corrected by geochemical model	25*	lake core	A/C; Cyperaceae	Van Campo *et al.*, 1996
d1	Balikun	Xinjiang	E86°40′ N41°56′	1580	C-14	No data	lake core	pollen percentage	Han, 1992
d2	Chaiwopo	Xinjiang	E87°15′ N43°25′	1115	C-14	8*	peat section	percentage	Shi, 1990
d3	Wulun Lake	Xinjiang	E87°00 N46°59′	no data	C-14	2*	lake core	C/A	Yang and Wang, 1996
d4	Boston Lake	Xinjiang	E86°40′ N41°56′	1048	C-14	4*	lake section	percentage; pollen concentration	Xu, 1998
d5	Manas Lake	Xinjiang	E86°00′ N45°45′	257	C-14	7*	lake core	A/C; pollen influx	Sun *et al.*, 1994
d6	Aibi Lake	Xinjiang	E82°35′ N44°54′	194	C-14	2* organic carbon	lake section	pollen percentage	Wu *et al.*, 1996

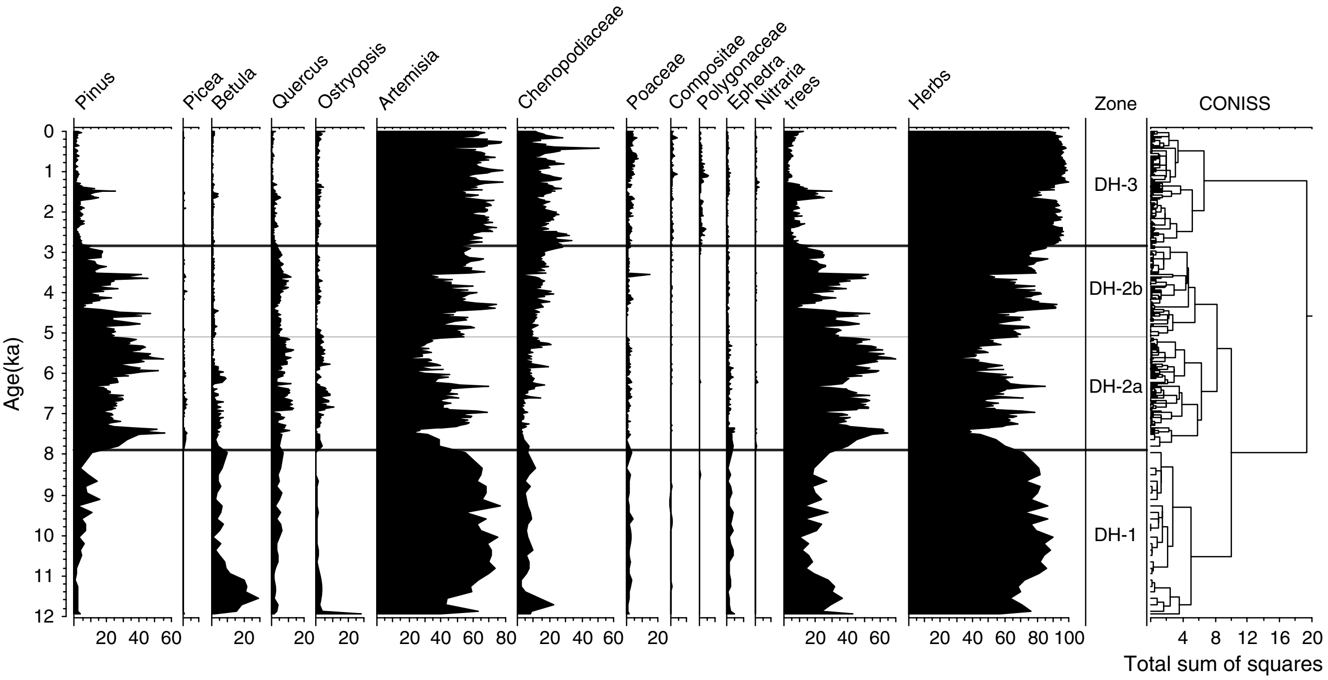

Fig. 4. Summary percentage pollen diagram from Daihai Lake (a6), Inner Mongolia (redrawn from Xiao et al., 2004).

pollen record that is representative of the pollen sites from the eastern part of Inner Mongolia (Fig. 4). At Daihai Lake, pollen assemblages are dominated by herbs and shrub pollen typical of arid conditions at 10.3 – 8 ka (1 ka = 1000 cal year BP), with ~65% *Artemisia*, ~10% Chenopodiaceae and 5% *Ephedra*; tree pollen is about 20% during this interval, mostly from *Pinus*, *Betula*, and *Quercus*. Between 8 and 5 ka, tree pollen reaches the maximum level of 40–60% for the entire Holocene and is characterized by *Pinus* (20–50%), *Quercus, Betula* and *Ulmus*. From 5 to 3 ka, tree pollen decreases to <20%, while Chenopodiaceae increases gradually from 10 to >20% and *Artemisia* increases to its Early Holocene level of ~65%. After 3 ka, pollen assemblages are dominated by consistently high *Artemisia* (~70%) and Chenopodiaceae (~20%), with some increases in Poaceae (to ~8%) (Xiao *et al.*, 2004). Vegetation around Daihai Lake changed from steppe at 10–8 ka, through *Pinus*- and *Quercus*-dominated steppe woodland (steppe forest) at 8–3 ka, to desert steppe after 3 ka. This vegetation sequence suggests climate changed from a dry climate in the Early Holocene, through a moist Mid-Holocene, to drier conditions in the Late Holocene. These vegetational and climate interpretations are quite similar to the original interpretation in Xiao *et al.* (2004) and different from another core at the same lake (Li *et al.*, 2004).

The Sanjiaocheng site (a8) is an exposed section in a dried-up lake basin in western Inner Mongolia, which is located near the present-day boundary between desert and steppe. At 11.6–7 ka, conifer tree pollen, mainly from *Sabina* (40–60%), *Picea* (up to 80%) and *Pinus* (20–40%), dominates the pollen assemblages. There are also consistently high total pollen concentrations (Fig. 5; Chen *et al.*, 2006). From 7 to 3.8 ka, pollen assemblages are characterized by xerophyte pollen types, including *Nitraria* (up to 90%) at the expense of *Sabina* (<20%), *Picea* (<5%) and *Pinus* (<10%). Pollen concentration is at the lowest level for the entire diagram at this interval. After 3.8 ka, pollen assemblages are dominated by Chenopodiaceae (up to ~40%), Poaceae (~30%) and *Artemisia* (~20%), with large fluctuations both in pollen percentages and in concentration (Chen *et al.*, 2006). Vegetation around Sanjiaocheng changed from steppe at 11.6–7 ka (pollen from *Sabina*, *Picea* and *Pinus* were likely transported by river from the Qilian Mountains due to stronger summer monsoon precipitation (Zhu *et al.*, 2003), through desert or desert steppe at 7–3.8 ka, to desert after 3.8 ka. This vegetation sequence indicates change from a wet climate in the Early Holocene, through a dry Mid-Holocene, to variable conditions in the Late Holocene.

Other pollen records from Inner Mongolia show diverse Holocene vegetation patterns. During the Early Holocene, pollen assemblages are dominated by *Betula*, *Picea*, and *Ulmus* in the southeast, but by *Artemisia*, with some *Picea* and *Abies* in the northwest. At 7–5 ka, during the Middle Holocene, pollen diagrams from the east and south tend to be dominated by *Artemisia* with some tree pollen, while those further north and west are dominated by tree pollen, including *Betula*, *Quercus*, *Ulmus*, and *Pinus*. In the Middle Holocene, pollen assemblages from eastern Juyanze are characteristic of *Artemisia.* After 5 or 4 ka, pollen assemblages change to *Artemisia*-dominated, with some tree pollen, in the east to *Artemisia* or Chenopodiaceae in the west (Li *et al.*, 1992;

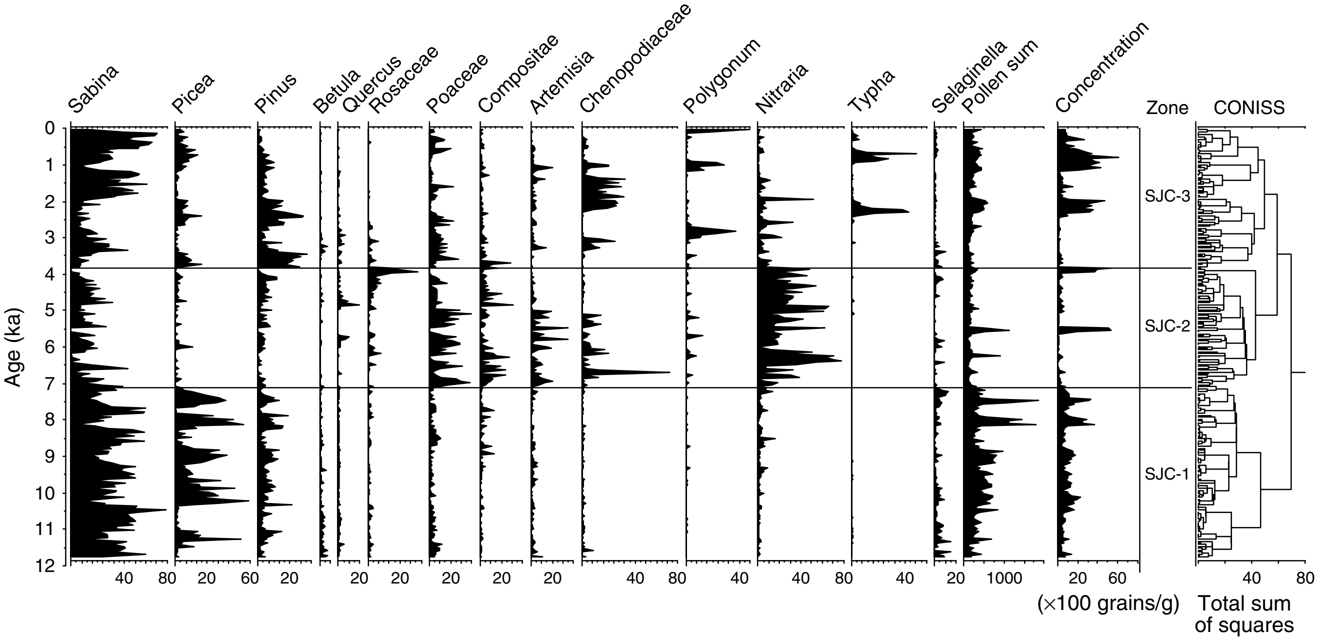

Fig. 5. Summary percentage pollen diagram from Sanjiaocheng (a9), Inner Mongolia (redrawn from Chen et al., 2006).

Yang and Wang, 1996; Wang and Sun, 1997; Liu *et al.*, 2002; Shi and Song, 2003; Ma *et al.*, 2003; Herzschuh *et al.*, 2004). Vegetation around Haoluku, Xiaoniuchang and Huangqihai changed from forest in the Early Holocene, through forest steppe during the Middle Holocene, to steppe forest in the Late Holocene. Vegetation at Hulun Lake, Diaojiao Lake, Chasuqi, Hongshui River and eastern Juyanze changed from steppe forest (or desert in eastern Juyanze which is situated further west) in the Early Holocene, through forest steppe or desert steppe in the Middle Holocene, to steppe/desert in the Late Holocene. These vegetation sequences indicate climate changed generally from a wet climate in the Early–Middle Holocene to drier conditions after 7 ka at eastern sites, but at western sites from a dry climate in the Early Holocene, through a moist Mid-Holocene, to drier conditions in the Late Holocene.

In the eastern part of Inner Mongolia (Hulun Lake, Xiaoniuchang, Huangqihai, Daihai, Diaojiaohai, and Chasuqi), the vegetation changed between steppe, forest steppe, and forest. However, for the sites in the west, where there were no forests throughout the Holocene, vegetation switched between steppe, desert steppe, and desert. Tree pollen accounts for significant portions of total pollen in the diagrams from Sanjiaocheng and Hongshui, suggesting that they were transported mainly by rivers from the Qilian Mountains, over 200 km south of these sites (Zhu *et al.*, 2002; Zhu *et al.*, 2003). Higher tree pollen abundance reflected either real change in mountainous vegetation or an increase in pollen transport, for example, due to stronger summer monsoon precipitation (Zhang *et al.*, 2000; Zhu *et al.*, 2002; Ma *et al.*, 2003; Ma *et al.*, 2004). Some sites in the east (Haoluku, Xiaoniuchang, and Huangqihai) show Holocene maximum moisture in the Early–Middle Holocene, while it occurred during the Middle Holocene at other sites. This indicates a time-progressive climate gradient from east to west and from south to north. After 4 ka, almost all the records indicate a drying trend, except at Hunlun Lake which reflects a wet and fluctuating climate after 4 ka.

4.2 Northwest Loess Plateau

Seven records are available from the northwest Loess Plateau that span the entire Holocene (sites b1–b7). Dadiwan (b5) is representative of the pollen sites in this region, and has a high sampling resolution of ca. 50 years (Fig. 6; An *et al.*, 2003). At 10–8.5 ka, the pollen assemblages are dominated by *Artemisia* (30%) and other Asteraceae (30%). From 8.8 ka to 6.4 ka, the pollen assemblages are characterized by up to 90% tree pollen, mostly from *Pinus* (up to 90%), with some *Betula*, *Ulmus*, and *Quercus.* After 6.3 ka, the pollen assemblages are dominated by Poaceae (up to 80%), Asteraceae, *Artemisia*, and Chenopodiaceae. Vegetation around Dadiwan changed from a steppe desert at 10–8.8 ka, through a *Pinus*-dominated steppe woodland (steppe forest) at 8.8–6.4 ka, to desert steppe after 6.4 ka. This vegetation sequence suggests climate change from a dry climate in the Early Holocene, through a moist Mid-Holocene, to slightly dry conditions in the Late Holocene.

At Midiwan (b3), in the desert–loess transition zone, the pollen diagram shows a different pattern of Holocene vegetation and climate changes. Vegetation changed from sparsely wooded grassland, consisting mainly of *Thalictrum*, Cyperaceae, *Betula*, and *Quercus* at 11.5–8.5 ka, through a

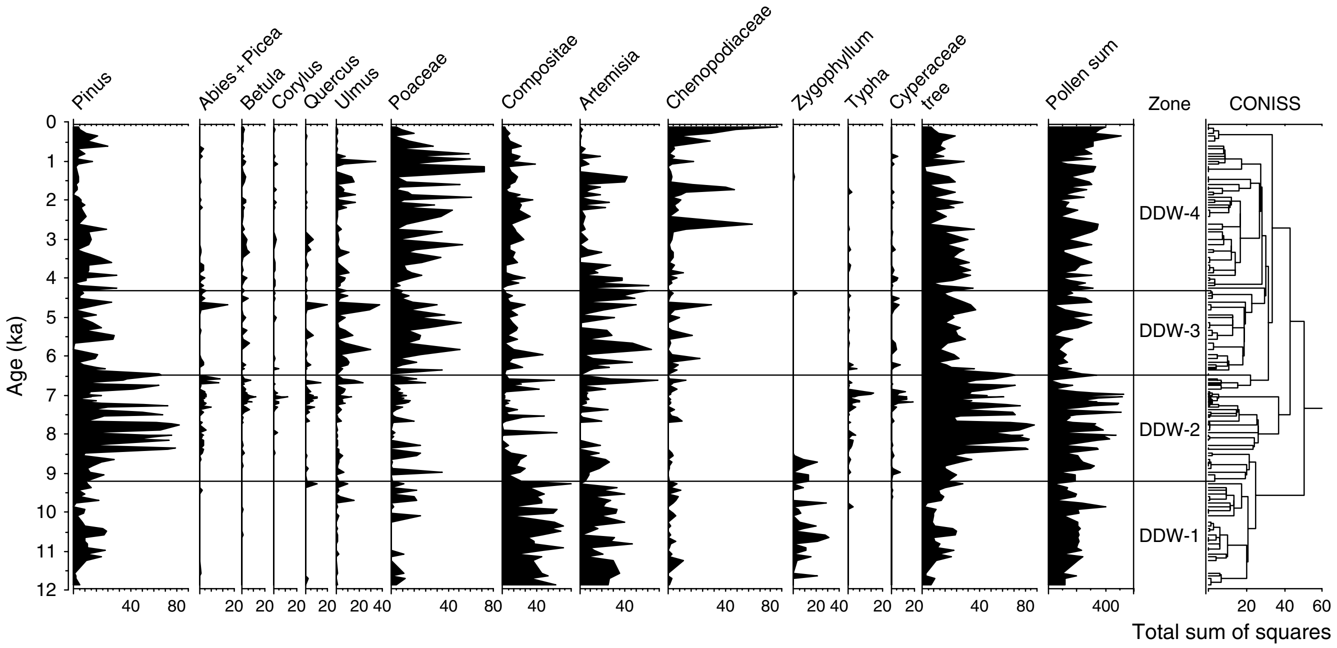

Fig. 6. Summary percentage pollen diagram from Dadiwan (b5), northwestern Loess Plateau (redrawn from An et al., 2003).

desert-steppe composed of *Artemisia* and Chenopodiaceae during 8.5–5.3 ka, to a humid steppe with some tree pollen at 5.3–3.2 ka, and finally to *Artemisia*-dominated desert steppe after 3.2 ka (Li *et al.*, 2003b). This vegetation sequence indicates climate changed from a warm and humid Early Holocene, through a dry Mid-Holocene, a wet early Late-Holocene, and drier conditions in the Late Holocene.

The pollen diagrams from other sites show that between 12 and 9 or 8.5 ka the pollen assemblages mainly contain Chenopodiaceae, *Artemisia*, *Reaumuria* or *Ephedra*, Compositae, and *Ranunculus*, with some tree pollen from *Pinus*, *Picea, Abies*, and *Ulmus.* These likely grew in the loess river terraces and valleys. From 9 or 8.5 to 6 ka, pollen assemblages are characteristic of *Quercus*, *Betula*, and *Pinus* at the sites in river valleys and terraces (Fuping, Dadiwan, and Shujiawan). At other sites *Artemisia*, Chenopodiaceae, Asteraceae, and Poaceae are the main pollen types. Pollen assemblages from the southeast site of Yaoxian are dominated by *Polygonum*, Lamiaceae, *Ulmus*, *Quercus*, and *Betula*, showing a different herb component from other sites. After ~5 ka, drought-tolerant plants such as Chenopodiaceae and *Ephedra* dominated (Sun and Zhao, 1991; Wang *et al.*, 1991; Gao *et al*, 1993; An *et al.*, 2003; Li *et al.*, 2003a). Vegetation around these sites changed from desert steppe before 9 or 8.5 ka, through shrub steppe or steppe with sparse trees from 9/8.5 to 6 ka, to desert steppe or semi-desert over the last 5 ka. At the sites in the river valleys and terraces, vegetation changes are somewhat different, transitioning from steppe/forest and steppe/steppe with sparse trees, through forest, to steppe or forest steppe. Climate was dry during the Early Holocene before 9/8.5 ka, became wet from 9/8.5 to 6 ka, and was dry again after 5 ka.

4.3 Northern Tibetan Plateau

Six pollen diagrams from the northern Tibetan Plateau (from c1 to c6) were used for this synthesis. In the pollen diagram from Qinghai Lake (Fig. 7; Shen *et al.*, 2005), pollen assemblages are dominated by *Artemisia* (~60%), tree pollen (~20%), Poaceae (~10%), and Chenopodiacece (~10%) at ~11 ka. At 11–4 ka, *Artemisia* decreases to less than 40%, *Pinus* increases up to ~30%, and *Betula* is up to 20%. The highest pollen concentrations exists in this zone. After 4 ka, *Artemisia* increases again (up to 80%) and *Pinus* decreases to 15–0% (Shen *et al.*, 2005). Vegetation around Qinghai Lake changed from steppe in the period before the Holocene, through steppe forest at 11–4 ka, to *Artemisia* – dominated steppe. This vegetation shift indicates a dry climate before the Holocene, a wet climate in the Early- and Mid-Holocene, and a dry climate in the Late Holocene.

Pollen assemblages from other sites (Dunde ice core, Selin Co, Sumxi Co, and Bangong Co) from this region are dominated by *Artemisia* and are characterized by higher pollen concentrations and higher A/C ratios during the Early – Middle Holocene. At Selin Co, Sumxi Co, and Bangong Co, this assemblage type lasted until 6.8 ka, with a peak A/C ratio between 8.4/8 and 7.4/6.8 ka. At Dunde, it lasted until 4.5 ka. After that period, *Artemisia*, Chenopodiaceae, *Ephedra*, and *Nitraria* dominate the pollen assemblages. Arboreal pollen was never the main component throughout the Holocene at any of the sites (Sun *et al.*, 1993; Van Campo *et al.*, 1993; Van Campo *et al.*, 1996; Liu *et al.*, 1998), except at Qinghai Lake (the easternmost site in this region) and Selin Co (the southernmost site). Vegetation switched between desert, desert steppe, and steppe. The abundant tree pollen at Selin Co during the Late Holocene probably resulted from aerial

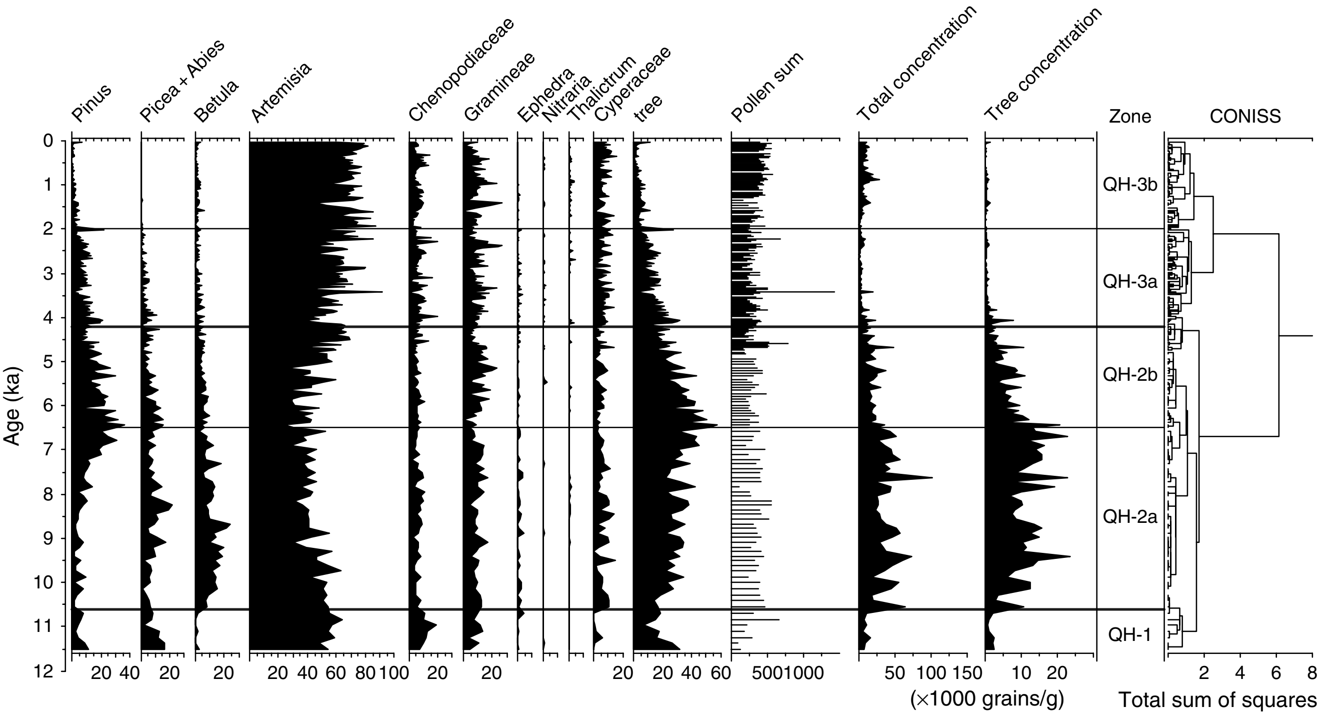

Fig. 7. Summary percentage pollen diagram from Qinghai Lake (C1), northern Tibetan Plateau (redrawn from Shen et al., 2005).

transport from the south and east when the monsoon wind was stronger, instead of indicating local trees. These sites show the Early – Middle Holocene had a consistently wet climate, and there was a progressive drying trend during the Late Holocene.

Our pollen analysis results from Hurleg Lake (c2) in the Qaidam Basin are in sharp contrast to the records from other sites, including Qinghai Lake (only ~300 km to the east) (Fig. 8; Zhao *et al.*, 2007). In general, *Artemisia*,

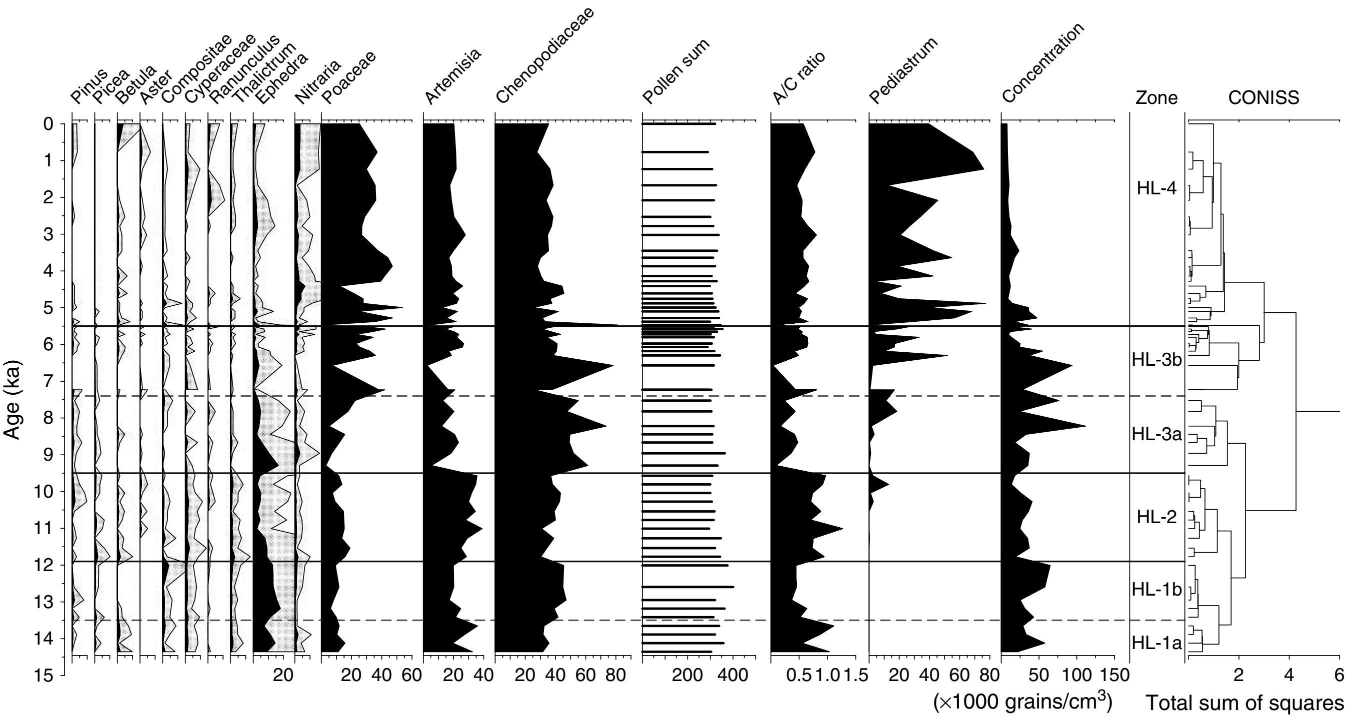

Fig. 8. Summary percentage pollen diagram from Hurleg Lake (C2), northern Tibetan Plateau (Zhao et al., 2007).

Chenopodiaceae, and Poaceae were the dominant pollen types at Hurleg Lake, with relatively low *Ephedra* and *Nitraria* pollen percentages. Pollen assemblages dating to before 9.5 ka are characterized by higher *Artemisia* (~35%), leading to higher A/C ratios. At 9.5–5.5 ka, Chenopodiaceae reaches the maximum (~80%) for the entire Holocene, with low and fluctuating A/C ratios. Poaceae starts to increase during this period. After 5.5 ka, pollen assemblages are dominated by consistently high Poaceae (30–40%), and Chenopodiaceae decreases to 35%. Vegetation around Hurleg Lake changed from *Artemisia*-dominated desert steppe before 9.5 ka, through Chenopodiaceae-dominated desert at 9.5–5.5 ka, and back to desert steppe after 5.5 ka. This vegetation sequence indicates that after a wet climate before 9.5 ka, a dry and variable climate occurred in the Early- and Mid-Holocene, and a wet climate returned after 5.5 ka.

4.4 Xinjiang Region

Six pollen sites from Xinjiang were selected to discuss changes in fossil pollen assemblages during the Holocene (Sites d1–d6). A summary pollen diagram from Manas Lake (d5) shows the general pattern of pollen trends in this region (Fig. 9; Sun *et al*, 1994). At 9.5–7.5 ka, the pollen assemblages are characterized by higher *Artemisia* (up to 55%) and the highest A/C ratios. From 7.5 to 4.3 ka, Chenopodiaceae increases (to 45%), *Artemisia* decreases from 40 to 30%, and Poaceae increases to ~5%. After 4.3 ka, *Artemisia* continues at 40% and Chenopodiaceae increases to 50%. Vegetation around Manas Lake changed from desert steppe before 7.5 ka, through a transition from desert steppe to steppe desert at 7.5–4.3 ka, to desert after 4 ka. This vegetation sequence indicates climate variation from a slightly dry climate in the Early Holocene, through a drying period in the Mid-Holocene, to a very dry climate in the Late Holocene.

Pollen assemblages at sites d1, d3, d4, and d6 show that vegetation changed between desert, desert steppe, or steppe during the Holocene (Han, 1992; Yang and Wang, 1996; Wu *et al*., 1996; Xu, 1998), based on criteria proposed by Li (1996). In these criteria, desert is defined by Chenopodiaceae pollen ratios ranging from 35 to 55%. Chenopodiaceae is <35% in desert steppe and occurs in lower percentages than *Artemisia.* Chenopodiaceae and *Artemisia* pollen, together accounting for less than 35% of total pollen, indicates steppe. Desert or desert steppe dominates the assemblages at these sites from the beginning of the Holocene until 9.5/8.5 ka. Vegetation was dominated by *Artemisia* steppe at the expense of Chenopodiaceae or *Betula*, *Salix*, *Picea*, *Ulmus*, and *Populus* (only at Chaiwopo) from 9.5/8.5 to 4.5/3 ka (Shi, 1990), while desert returned to dominance after 4.5/3 ka. Vegetation reconstructions from fossil pollen data indicate that the climate was dry during the first two thousand years of the Holocene and became wetter from 9.5/8.5 to 4.5/3 ka. All the records indicate that effective moisture decreased after 4 or 3 ka, though with some fluctuations.

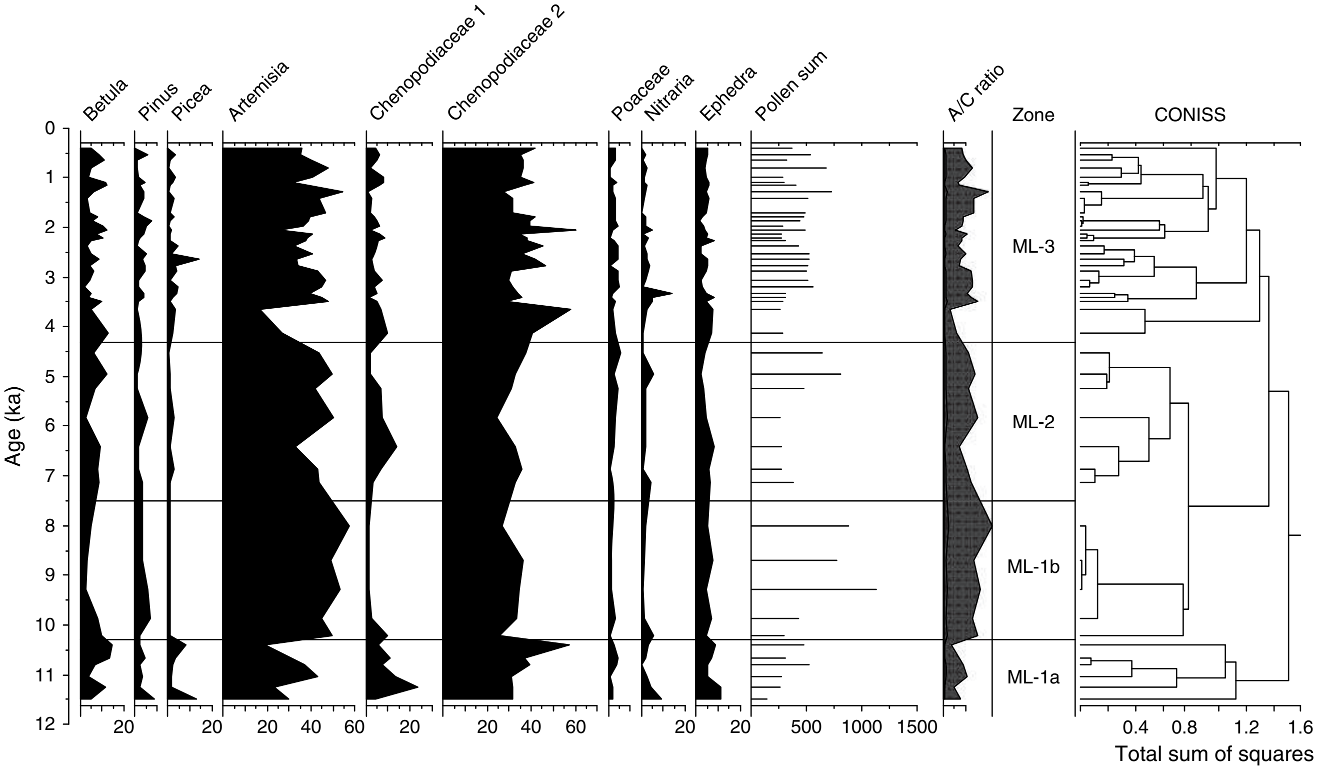

Fig. 9. Summary percentage pollen diagram from Manas Lake (d5), Xinjiang (redrawn from Sun et al., 1994).

5. Holocene Climate Changes in Arid and Semi-arid China

5.1 The Holocene Climate Optimum

In the arid and semi-arid regions of China, a climate optimum in the Mid-Holocene, if it existed, should be reflected in the highest moisture conditions of the Holocene. The timing of this optimum period is highly variable according to the pollen records we review here (Fig. 10). In Inner Mongolia, it appears to have occurred during the Early and Middle Holocene at most sites. In the northwestern Loess Plateau, the maximum moisture occurred during the Middle Holocene (8.5–5 ka). On the northern Tibetan Plateau (Hurleg Lake is apparently an exception), moisture reached its maximum in the early Mid-Holocene. In Xinjiang the maximum moisture occurred briefly in the Mid-Holocene.

This inconsistency in timing of maximum moist Holocene climate either is due to poor dating and limited sampling resolution or is a real feature of regional climate changes in northern and northwestern China. In many places in the southeastern Eurasian continent, effective moisture is determined by the Indian Monsoon and Southeast Asian summer monsoon precipitation. However, further west, in Xinjiang for example, the westerlies could be more important, if not the determining factor, in effective moisture.

5.2 Long-Term Holocene Climate Trends Vs. Wet–Dry Climate Oscillations

Pollen records from the four regions reveal different vegetation and wet–dry changes during the Holocene (Fig. 10). All the sites in Inner Mongolia are situated close to the modern summer monsoon limit or outside the monsoon. Most sites in eastern Inner Mongolia show a dry climate after ~6 ka following the Early Holocene maximum moisture conditions, while at western sites the climate was dry in the Early Holocene, wet in the Middle Holocene and dry again in the Late Holocene. In the northwestern Loess Plateau, all the sites appear to show wet–dry oscillations, from an initial dry climate to wet Middle Holocene and then back to a dry climate in the Late Holocene. In the northern Tibetan Plateau, all sites are situated near or outside the extreme limits of the summer monsoon influence and indicate a wet climate in the Early and Mid-Holocene until 6–4.5 ka, when a drying trend started. Xinjiang is under the control of the westerlies, where a wet period occurred briefly during the early Mid-Holocene at most sites.

Most sites that are strongly influenced by summer monsoons show a continued drying trend during the Holocene, as the summer monsoon intensity decreased in accord with the solar radiation maximum in the Early Holocene (Kutzbach and Guetter, 1986; An *et al.*, 2000; Morrill *et al.*, 2003; Herzschuh, 2006) and the dry winter monsoon wind strength increased. However, at other sites apparent multiple wet–dry oscillations that cannot be explained by orbital forcing alone might have been caused by the interactions between the southeast summer monsoon and the westerlies.

The inconsistency of climate patterns indicated by these records shows the complexity of Holocene climate change, especially near the northern limit of the summer monsoon influence. We find that a model that simply follows the insolation trend and monsoon intensity during the Holocene cannot be supported in arid and semi-arid regions of China. At many sites, the summer monsoon is not the dominant

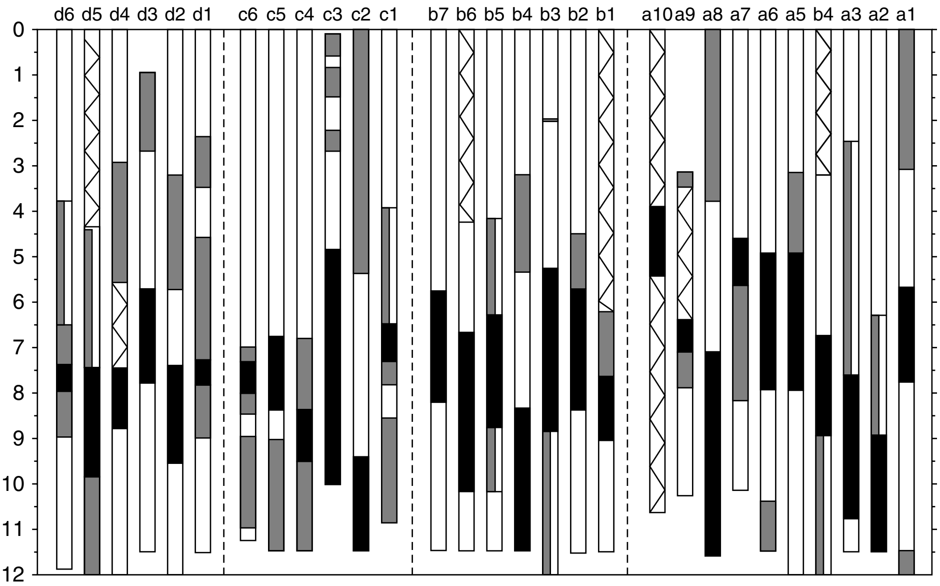

Fig. 10. Correlations of wet–dry climate intervals across arid and semi-arid China. Black indicates the maximum moist intervals, white the driest intervals, gray the intermediate moisture conditions, and wave-line the fluctuated moisture conditions.

control of regional and local climate, which is unlike sites in southeastern and southwestern China (e.g., Dongge Cave, Wang *et al.*, 2005). Also, on the northern Tibetan Plateau, local topography may be important in modifying the spatial pattern of climate changes, for example, Hurleg Lake appears to be the most noticeable exception among all the sites reviewed. It is also the only site from the Qaidam Basin. The contrasting pattern suggests the importance of interaction between subtropical (monsoon), mid-latitude (westerly) atmospheric circulation systems, and local topography in determining regional climate. The Qaidam Basin is well known for its high potential evaporation, so enhanced evaporation could overtake higher monsoon precipitation and thus reduce effective humidity during the Middle Holocene optimum.

5.3 Human Impact on Vegetation

In the arid and semi-arid regions of China, both climatic drying and human disturbance may have contributed to Late Holocene vegetation change. However, the pollen evidence for human impacts on Chinese vegetation and how the anthropogenic signal can be distinguished from the climatic signal is still to be explored (Liu and Qiu, 1994). Although some pollen records are available, as discussed above, relatively few have the necessary resolution and sensitivity to permit a high-resolution Late Holocene climate change reconstruction and extraction of a human signal. For example, many researchers argue that human activities caused vegetation deterioration, especially in the Loess Plateau and Ordos Plateau (e.g. Shi, 1981; Ren and Beug, 2002), but the pollen records are scarce or limited by inadequate dating control, coarse sampling intervals and insufficient taxonomic details (Liu and Qui, 1994).

Despite these limitations, some pollen records from various parts of dry and semi-dry China do imply human impacts on vegetation, though without clear evidence of short-term climatic fluctuations during the Late Holocene. In Inner Mongolia, vegetation around Daihai Lake changed from *Pinus*- and *Quercus*-dominated steppe woodland (steppe forest) at 8–3 ka, to desert steppe after 3 ka. The sharp decrease in tree pollen abundance could also have been induced by human activity, such as deforestation, and would correspond with archeological records. These sharp changes also occurred at other sites. At Haoluku, in Inner Mongolai, tree pollen decreases and *Artemisia* increases after 2 ka. At Dadiwan, in the Loess Plateau, there is a large decrease in tree pollen and an increase in Poaceae after about 2 ka. At Qinghai Lake, on the northeastern Tibetan Plateau, there is a similar tendency after 2 ka. These records suggest that human activity could, along with climate, have had an impact on vegetation change, especially after 2 ka. However, more data and dates will be needed to evaluate the relative contributions between climatic and anthropogenic factors in vegetational changes during the Late Holocene, including more palynological records and increased evaluation of historical records (Liu and Qiu, 1994).

6. Concluding Remarks

1. Pollen data for north and northwest China show various vegetation responses to Holocene climate changes. Vegetation at most sites in Inner Mongolia switches between forest, forest steppe, and typical steppe, except at the westernmost sites. Vegetation in the northwestern Loess Plateau switches between desert steppe, steppe, and steppe forest, with corridor forests in loess valleys. On the northern Tibetan Plateau vegetation is characterized by steppe, desert steppe, or desert. An exception is the Qinghai Lake region. This area was dominated by tree pollen during the Early and Mid-Holocene due to its location on the eastern edge of the Plateau where it is strongly influenced by the summer monsoon. In Xinjiang, pollen assemblages show changes between desert, desert steppe, or steppe during the Holocene.
2. The highest moisture interval during the Holocene (the so-called Holocene climate optimum) occurred in the Early and Mid-Holocene in eastern Inner Mongolia, but appeared to occur later during the Mid-Holocene at sites in the west (northern Tibetan Plateau and Xinjiang). As a result, the sites in the eastern half of the region show a unidirectional drying trend after the Early Holocene moisture maximum, while in the western half there are wet–dry climate oscillations from an initial dry climate to a wet climate and dry again. Therefore, the general pattern, as indicated by insolation-driven monsoon intensity, appears in some, but not all, regions.
3. The *Artemisia*-to-Chenopodiaceae (A/C) ratio appears to be a useful pollen index for climate interpretation, but it may not be applicable to sites with significant tree pollen representation. Also, caution is warranted in using pollen concentrations to represent vegetation cover and, hence, effective moisture, as high Chenopodiaceae pollen production and variable sediment-accumulation rates may distort climate interpretations. Increased abundance of desert plants, such as *Nitraria*, may respond to an increase in the groundwater table under wet climate rather than expansion of desert vegetation in dry climate.
4. The complex climate patterns during the Holocene in arid and semi-arid China suggest regional climate responses to large-scale climate forcing. The southeast Asian summer monsoon appears to dictate the climate history of most parts of China, but regional differences are apparent due to interactions of competing forcing factors (the monsoon, westerlies, and topography).
5. Human activity could be an important factor affecting vegetation change. More historical and palynological data and dates will be needed to evaluate the relative contributions between climatic and anthropogenic factors in vegetational changes during the Late Holocene.

Acknowledgments

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Part III

THEORETICAL PERSPECTIVES

6

Variation in Late Quaternary central Asian climates and the nature of human response

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Abstract

Long-term climate cycles related to gradual shifts in solar insolation, as well as shorter-term shifts in volatility and equability, are important components of cultural evolution. However, major rapid climate change episodes related to Dansgaard–Oeschger cycles and Heinrich Events apparently had the most dramatic impact on cultural change in arid China during the Late Quaternary. We propose three models relating environmental change with human adaptive shifts in the region: (1) a shift to broad-spectrum foraging may be related to a reduction in high-ranked resources during the Last Glacial Maximum (LGM); (2) millet domestication probably began in the northern margin of wild millet distribution as it began to contract during the Pleistocene/Holocene transition; and (3) desertification may have been accelerated and enhanced during the Late Holocene in some areas of arid China by the development of camel-based pastoralism. We propose a number of possible tests of these models.

1. Introduction

Human foragers must deal with two distinct but interrelated types of environmental change. First, change in climatic conditions directly influences people most obviously in terms of annual variation in the overall distribution of precipitation and temperatures as well as less obviously in terms of variation in seasonality. These variations in short-term weather patterns affect the productivity of the resources utilized by foraging groups and, hence, alter a variety of behaviors such as group size, mobility, storage, and choice of winter sites. Second, longer-term climatic change more indirectly, but more fundamentally, affects people by altering both the distribution and the composition of the resource base. Change in the basic environmental structure in which people live, and upon which annual variations are imposed, alters the selective context in which people operate, and alters, on a permanent basis, the behavioral strategies which are most successful. Recognition of how these two types of changes modified the behavior of modern human foragers in arid Eurasia after about 50 ^{14}C ka is critical in understanding how the material record of this behavior may best be interpreted. This is particularly important for this region, since environmental changes were not ameliorated by adoption of agriculture and pastoralism until well into the Holocene.

What follows here consists essentially of two parts. First, for those less familiar with climate change cycles, we review some of the salient features that most directly impact cultural evolution. Second, we propose several models of human response to climate change events in arid China over the course of the last 40,000 years and present some testable implications of these models. The climate aspects of such a review necessarily are rather general in scope, but more detailed treatments of environmental change are available in the first section of this volume.

2. Part I – Late Quaternary Climate Change[1]

2.1 Short-Term Environmental Variance

Change in the variation of short-term climatic conditions (apart from the normal variance associated with daily to inter-annual variability) occurs primarily in terms of change in volatility and equability. Volatility is a measure of the year-to-year, decade-to-decade change in temperature and precipitation. Highly volatile climates are those in which variations are extreme; less volatile climates are those in which short-term variations are modest. The long-term average conditions are the same, but the range of variation differs considerably. During the Late Pleistocene and Holocene, climates have shifted between steady states of relatively high and relatively low volatility. In many cases, these differing steady states have lasted for more than a 1000 years before shifting rapidly to alternative steady states.

Equability is a measure of the relative difference in the length and intensity of climate on a seasonal basis. Highly equable climates are those in which there is relatively little difference in precipitation and, particularly, temperatures between one season and another. Mediterranean and coastal climates are often highly equable. Climates with low seasonal equability are characterized by warm summers and cold winters, and/or wet and dry seasons.

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[1] Parts of this and the following section were modified from Madsen (1999; 2000).

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Average annual precipitation and temperatures for systems with high and low equability may be similar, but their distribution is different. For human foragers in mid-latitude regions such as interior arid Asia, changes in equability alter the way people are able to utilize a given resource base. For example, such changes may prolong or shorten the growing season, or keep winter temperatures above freezing and allow the use of root crops and marsh resources that may normally be frozen.

On the whole, changes in volatility and equability were limited throughout most of the Holocene, at least in comparison to full-glacial conditions (e.g., Bond *et al.*, 1997; Mayewski *et al.*, 1997), and these kinds of short-term climate change likely had limited impact on later agricultural and pastoralist societies beyond that associated with normal inter-annual variations in weather. The full-glacial period (~20–12.5 ^{14}C ka, ~24–14.5 Cal ka) and the shorter Younger Dryas (10.9–10.1 ^{14}C ka, 12.7–11.6 Cal ka), on the other hand, are characterized by extreme climatic variability on at least a decadal level (e.g., Mayewski *et al.*, 1993; Stuiver *et al.*, 1995). As a result of this climatic volatility, during the LGM and the millennium or so of the Younger Dryas, foragers in western China were being whipsawed from one climatic extreme to another, often within periods of less than a decade. The variance of these extremes is considerably greater than that of the Holocene; indeed, the range of climatic variation from one decade to another was almost as great as the entire range of variation for the Late Wisconsin as a whole. The LGM and Younger Dryas environmental conditions also differed from climatic cycles that followed in seasonal equability (e.g., Zielinski and Mershon, 1997), as summers in the northern hemisphere were cooler (resulting in reduced evaporation), but winters were no colder and may even have been slightly warmer.

These climatic features of the LGM and Younger Dryas, and the environmental proxies that accompanied them, had important implications for the transition from foraging to agriculture and pastoralism (e.g., Richerson *et al.*, 2001; Bettinger *et al.*, this volume). The climatic volatility means that the availability of ephemeral plants, such as grasses, probably fluctuated in concert with the wildly fluctuating climatic conditions. Animal populations dependent on these ephemeral taxa may also have been maintained at reduced levels (or restricted in distribution) since episodes of drastic climatic change were followed by only limited recovery time. Mature individuals of less ephemeral plant species probably survived these rapid climate swings, but their seed production likely varied substantially, and immature individuals may not have survived. This variation in environmental proxies of full-glacial and Younger Dryas climates probably resulted in the maintenance of relatively low population densities, as late paleolithic foragers were repeatedly subjected to stress. The seasonal equability of these climatic episodes, on the other hand, may have prolonged the seasonal availability of food resources and reduced the need for storage through the winter months.

2.2 Long-Term Environmental Change

Climatic changes that are more fundamental, but more indirect in human terms, are those in which averages of temperatures and precipitation change on relatively long scales. These often exceed scores of generations and, hence, represent climatic change that operates outside the corporate memory of any foraging group. These changes are essentially permanent in terms of human lifetimes and lead to changes in the composition of plant and animal communities and in the distribution of other critical resources such as water. While changes in volatility and equability are types of climatic change which obviously also lead to change in the composition of the resource base, they do so in less fundamental ways than do changes in absolute temperatures and amount of available water, since the shorter-term changes are imposed upon these longer-term variations in climate.

These long-term climatic changes are related most directly to changes in the relative distance between the earth and the sun that varies with perturbations in the earth's orbit and axis and, hence, affects the amount of solar radiation reaching the earth's surface. These climatic changes operate on a number of different scales and, depending on where the earth is in each of these Milankovitch cycles, can reinforce or counteract each other. For Late Quaternary climates, the 19,000- and 23,000-year precession cycles and the 41,000-year obliquity cycles are particularly important (e.g., Grootes and Stuiver, 1997). Shorter-term (but still long in human terms) climatic cycles on millennial scales of about 6100 (Bond cycles) and about 1500 years (Dansgaard–Oeschger [D/O] cycles) have also been recognized in proxy records from ice cores and from cores taken from the ocean and larger continental lakes (Figure 1). As yet, it is not clear how these shorter-term cyclical variations may relate to the celestial mechanics which drive the longer cycles, although there is some suggestion that they are caused primarily by variation in solar output itself (e.g., Denton and Karlén, 1973; Finkel and Nishiizumi, 1997;

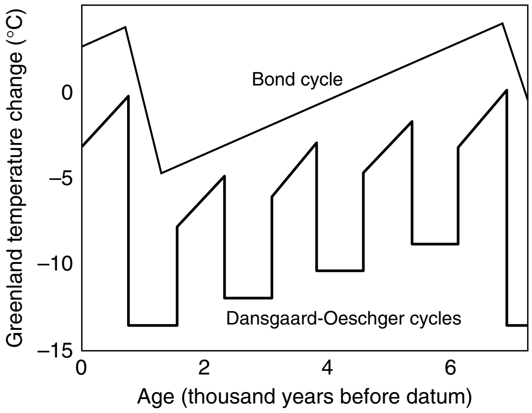

Fig. 1. Schematic outline of typical Bond and Dansgaard–Oeschger cycles during the last glacial period. Variance was reduced to 1–3° C during the Holocene (after Alley, 1998). Heinrich Events occur at the coldest point in each Bond cycle.

Björck *et al*., 2001; Bond *et al*., 2001; Neff *et al*., 2001; Kodera, 2002; Rahmstorf, 2003). However, there is no clear consensus currently, and a number of possible explanations for the cause of these shorter cycles, especially the D/O cycles and some shorter century-scale cycles, have been posited (e.g., Rind and Overpeck, 1993; McIntyre and Molfino, 1996; Clark *et al*., 1999; Keeling and Whorf, 2000; Clement *et al*., 2001; Broecker, 2003). In particular, there are large-scale climate changes correlated with stochastic events such as volcanic eruptions and catastrophic floodwater outflows that reduced or enhanced the underlying solar-based climate cycles (e.g., Magny and Bégeot, 2004). Three such events, related to the sudden collapse of proglacial Lake Agassiz, occurring about 10,850, 9900, and 7300 ^{14}C yr BP (about 12,850, 11,250, and 8100 Cal yr BP), fed large quantities of cold, fresh water into the North Atlantic, temporarily shut down the ocean conveyor system that largely structures Northern Hemisphere climates, and dramatically enhanced the scale of D/O cycles during these periods (Teller *et al*., 2002). A number of other similar floodwater events occurred throughout the Holocene but were of a smaller scale and had reduced impacts on climate.

Regardless of the cause, what is becoming increasingly clear is that the transitions between the steady-state conditions that characterize these millennial-scale cycles are relatively abrupt, often on the order of a decade or less, and certainly within the lifetime of an individual. In the North Atlantic, and apparently throughout the Northern Hemisphere (e.g., Sirocko *et al*., 1996; Schulz *et al*., 1999; Ding *et al*., 1998; von Grafenstein *et al*., 1999; Bianchi and McCave, 1999; Brown *et al*., 2000; Leuschner and Sirocko, 2000; Courty and Vallverdu, 2001; Noren *et al*., 2002; Burns *et al*., 2003; Gupta *et al*., 2003; Wang *et al*., 2003; Benson *et al*., 2003; Chen *et al*., 2006), the D/O cycles are synchronous and take a characteristic form (Alley, 1998). While they range in duration from 1000 to 2000 years, they average about 1500 years long (more precisely ~1470 years long [Rahmstorf, 2003]) and are initiated with a rapid rise in temperature in a matter of decades (5–8° C during the glacial period and 1–3° C during the Holocene), gradually return to moderate conditions over the course of ~1000 years and end with a rapid return to very cold temperatures prior to the start of a warming event which initiates a new cycle (Figure 1). Currently, 26 possible cycles can be defined for these detailed core records during the approximately 50,000 calendar years of modern human occupation in northern Eurasia (e.g., Rahmstorf, 2003). Longer-term, lower-frequency Bond cycles, also evident in these records, are characterized by overall cooling across a number of D/O cycles culminating in a coolest period associated with Heinrich Events, with these, in turn, followed by marked rapid warming (e.g., Alley, 1998). As Barton *et al*. (this volume) note, Heinrich Events may have been particularly critical in the evolution of foraging adaptations in arid China.

It is becoming evident that environmental change in western China is correlated with millennial-scale cycles evident in the ice core records, but all of the Late Quaternary cycles have yet to be recognized locally. This is probably due to a combination of factors, such as the relatively coarse nature of the local environmental record and the presence of other, longer cycles which may obscure local manifestation of millennial-scale fluctuations. Most of the Holocene cycles are becoming evident in proxy records from in or near arid western China (e.g., Zhu *et al*., 2002; Wang *et al*., 2005; Chen *et al*., 2006; Porter and Zhou, 2006) and will likely be more completely defined for older periods once more chronologically detailed and sensitive records, comparable to those from tree rings and lake varves, are available for the entire period of modern human occupation. Certainly, major and most minor D/O cycles spanning marine isotope stages (MIS) 3-1 can be easily recognized in high-resolution Asian records ranging from loess (Porter and An, 1995; Chen *et al*., 1997; Ding *et al*., 1999; Porter and Zhou, 2006) to ice cores (Thompson *et al*., 1997; Thompson *et al*., 2003) to speleothems (Wang *et al*., 2003; Zhang *et al*., 2004). As papers in the following section make abundantly clear, they can also be recognized in the archeological record of arid China. Madsen *et al*., in the summary section of this volume, provide one explanation of why that may be so.

Other, even shorter, climatic cycles, such as those associated with the El Niño-Southern Oscillation and the North Atlantic Oscillation, ranging in length from a few decades to several centuries, are also evident in a variety of proxy records and may also be related to variation in solar output (e.g., von Grafenstein *et al*., 1999; Chapman and Shackleton, 2000; Clement *et al*., 2001; Berger and von Rad, 2002; Kunzendorf and Larsen, 2002; Takahashi *et al*., 2003; Menking and Anderson, 2003; Gagan *et al*., 2004; Wang *et al*., 2005; Chen *et al*., 2006). Unfortunately, these shorter cycles are within the range of variation of most radiocarbon dates, and records of these events are difficult to correlate both with one another and with environmental and archeological changes.

3. Part II – Hypothesized Human Response to Climate Change in Arid China

As Madsen *et al*. note in the introduction to this volume, Chinese archeology has traditionally been primarily descriptive in nature and has been associated with the construction of history. As a result, there have been few attempts to create testable models of human adaptation in arid western China. Yet clarification of the way foragers responded to both long- and short-term climate cycles, and understanding why they did so in the manner they did, requires the elaboration of hypotheses that can be examined against the archeological record. Here, we present three hypothetical models that may help explain major changes in human behavior during the last 40,000 years. While these models are surely wrong in many details and may also require modification of some of their broader aspects, they represent an attempt to guide archeological research in western China in a way that moves it beyond simple history.

3.1 Upper Paleolithic Response to the Longer-Term Climate Cycles of MIS 3 and 2

After the appearance of anatomically modern humans in Eurasia after ~50 ^{14}C ka (e.g., Su, *et al.*, 1999; Ke *et al.*, 2001; Dolukhanov *et al.*, 2002), the initial major cultural change in interior China was the transition to an intensive hunting and gathering strategy that led, in turn, to the development of agriculture after ~10 ^{14}C ka. It seems likely this transition to broad-spectrum foraging was a response to environmental circumstances related to the dramatically shifting location and intensity of winter and summer monsoons. The environmental changes associated with MIS 3/2 are detailed in Section 2 of this volume, but, briefly, between about 40 and 25 ^{14}C ka, cool summers and higher precipitation created a system of large lakes and semi-aquatic environments in what are now the sand and Gobi deserts of western China. Increasing aridity thereafter completely desiccated many of these lakes, and dune fields began to build on the dried lake floors by 18 ^{14}C ka. The initiation of this dune building appears to correlate with the inception of Malan loess deposition. After about 13 ^{14}C ka, somewhat smaller lakes reappeared in many of the lake basins, with these shallow lakes lasting until shortly after 11 ^{14}C ka. This moist 13–11 ^{14}C ka interval was followed by a brief, but relatively intense, period of desiccation associated with the Younger Dryas, lasting from about 10.8 to after 10 ^{14}C ka, during which regional lakes again dried and loess accumulated rapidly. The remainder of the Holocene was characterized by alternating periods of lake desiccation and eolian activity and lake recharge/incipient soil development.

Throughout MIS 3/2, periods of soil formation are contemporaneous with high lake stands and presumably reflect periods of increased vegetative cover associated with increased available moisture-related widespread regional climatic change. This variation between periods of increased annual precipitation, rising lake levels, and soil formation, on the one hand, and aridity, lake desiccation, and erosion/loess deposition, on the other, is generally attributed to the strengthening and weakening of the summer monsoon (e.g., An *et al.*, 1991). Some caution is required in applying this interpretation to the pattern of climatic change in western China, however, because the area is at the northwestern limit of the warm–wet summer monsoon effect, and its role relative to that of the cold–dry winter monsoon remains unclear (see Zhao *et al.*, this volume). Nevertheless, we assume an association of depositional/erosional intervals with cold–dry winter monsoonal dominance and soil formation with warm–wet summer monsoonal dominance. It is clear, in any event, that whatever forcing mechanisms were involved, regional climate and environment changed dramatically during the interval in which complex hunter-gatherer adaptations developed in north China. Superimposed on this is a more long-term trajectory of declining mean productivity from the LGM to the present: good periods were steadily less productive, bad periods steadily worse.

The climatic sequence just outlined is a critical aspect of what we think is a tendency toward resource intensification relatively early in the Chinese Late Paleolithic. . .much earlier, and concomitantly more prolonged, than in many other areas of the world (but see Weiss *et al.*, 2004, among others). The broad-spectrum revolutions which characterize the Paleolithic-to-Neolithic transitions in these better-known areas of the world are thought to be related to a dramatic change in the resources available to hunter-gatherers at the close of the Pleistocene. With the shift to warmer and, more importantly, drier climatic conditions at the end of the last ice-age, the abundance of high-ranked, high-return resources was severely reduced and the diet-breadth enlarged significantly to include many lower-ranked resources such as seeds and other plant resources which previously had been largely ignored. Continued manipulation of these plants, and the technology associated with their procurement and processing, led ultimately to the development of agriculture. Theoretically (e.g., Stiner *et al.*, 2000), such intensification is a likely response to increases in human population or reduction in overall environmental productivity due to climate change. Intensification is a strategy in which efforts are made to increase the yield of certain resources by adding labor, thereby decreasing efficiency. Overall returns are increased, but at a cost. Intensification may involve broadening the diet to include resources requiring more processing (such as seeds), with greater investment in the technology that processing requires. Intensification may also be accomplished by focusing on a reduced number of resources or classes of resources.

Although data are limited for arid western China, a reduction in the numbers of high-return resources, particularly populations of large animals, occurred at the beginning of the LGM, much earlier than in many other areas of the world. The numerous broad shallow lakes that filled much of what are now the deserts of China began to dry up, and extensive grasslands were dramatically reduced. While this likely resulted in marked reduction in the numbers and kinds of herd animals these grasslands supported, information on large mammal biogeography is limited for this period and is itself a key inference that needs to be confirmed. We hypothesize people in arid China may have reacted to these changes in the following way.

Brantingham *et al.*, (2003) suggested that prior to ~25 ^{14}C ka, modern human foragers followed a “random walk” pattern of landscape utilization, focusing on the collection of high-ranked resources, primarily large herd animals, evenly scattered over widespread grassland ecosystems. That is, MIS 3 foragers were essentially composed of small, highly nomadic, family groups wandering broadly across a nonpatchy landscape. As yet, there are only modest data to support such a model, and MIS 3 environments were certainly patchier than the model requires. Nonetheless, as lakes shrank and grasslands dried, the environmental situation certainly changed by the beginning of the LGM when populations above 38° N latitude in China were greatly reduced (Lu, 1999; Bettinger *et al.*, this volume; but see Barton *et al.*, this volume), and most of Siberia depopulated (Goebel and Slobodin, 2001; Goebel, 2002).

The elimination of lake-margin ecosystems and the reduction in grasslands between them by ~20 ^{14}C yr ka may have forced a shift to a high-mobility strategy in which small groups of hunter-gatherers had to move relatively long distances between islands of resource availability. These widely scattered oases supported an array of high- to low-return resources, none of which was very abundant due to the limited size of the resource islands. At each stop, these hunter-gatherers would have dipped well into lower return resources, including many plants and small animals, because of the high cost of transport across the deserts to the next oasis. Thus, during the LGM, people began to use the lower-return plants, which were to become the focus of the agricultural revolution, and to develop the technology to procure and process them. However, these lower return resources continued to be only a small part of the diet, because their abundance was also limited in the vicinity of these small resource patches. Throughout northeast Asia at about the LGM, core and blade technology was replaced by much more costly microlithic technology providing stone insets for composite bone armatures used as points and knives. This change signals intensification, but of a type in which increased labor is focused on a few high-ranked prey only available for short periods of the year, but critical for survival (Elston and Brantingham, 2002). This strategy is typical of arctic and subarctic regions where game aggregates in summer but is nearly absent in winter (Holly, 2005). Whatever the cause of the microlithic transition, it was rapid and extensive, occurring throughout northeast Asia from Siberia to northern China at about the same time (Lu, 1998; Li, 1999; Goebel, 2002; Brantingham *et al.*, 2004; Barton *et al.*, this volume). Some of the ubiquitous aceramic microlithic scatters in the Tengger desert could date to the post-LGM period, but the difficulty of recognizing sites of this age is compounded by the long persistence of microlithics and lack of time-marking technological or morphological elements within this tradition (Aldenderfer and Zhang, 2004). In short, these highly mobile hunter-gatherers probably pursued a more complex diet combining both broad-spectrum and narrowly focused diets that included an array of high- to low-return resources.

While shallow lakes and lake-margin habitats returned to the deserts of central China about 13–11 ^{14}C ka, the extensive grasslands and the array of herd animals which characterized the area before 20 ^{14}C ka did not return in any significant way (Xia *et al.*, 2002). Thus, the dynamics between the abundance and distribution of higher and lower return resources changed mobility patterns significantly. Oases in the desert were considerably enlarged, and while the abundance of lower return plants and animals increased dramatically, the abundance of higher return resources continued to be limited. In many locations, the abundance of these moderate return rate resources was sufficient to support a virtual sedentary existence or, at the very least, much reduced mobility patterns. There was no economic incentive to move often, since transport costs associated with the procurement of high-return resources at separate lake-margin oases reduced the overall average to those equal to or lower than more moderate, but more abundant, resources at single lake/marsh habitats.

In the Tengger Desert area, for example, the archeological record of the terminal Pleistocene Helan Period (12.7–11.6 ^{14}C ka), when lakes, marshes, and uplands of the more mesic interval provided a variety of plants and animals (Madsen *et al.*, 1996), is characterized by increased numbers of sites and larger, more diverse, lithic assemblages, suggesting a broad diet but relatively low residential mobility (Elston *et al.*, 1997; Madsen *et al.*, 1998; Elston *et al.*, 2005). In short, diets continued to be broad, but the diversity of resources in the diet was significantly reduced since high-return, but comparatively rare, resources were quickly eliminated in any one area. Thus, people were focused on the procurement and processing of many of the plants that ultimately became the basis for the agricultural revolution in China as well as on an elaboration of the technology associated with that procurement and processing. Unfortunately, for the purposes of testing this model, mere parching, winnowing, and boiling makes millet palatable and it does not need to be ground before eating. Thus, the presence of abundant ground stone, one of the common hallmarks of intensive seed use elsewhere (e.g., Rhode *et al.*, 2006), is of little use in evaluating the early seed manipulation in arid China. While ground stone is occasionally identified in Late Upper Paleolithic sites (e.g., Elston *et al.*, 1997), early grinding stones are rare throughout China, even during the northern China Early Neolithic when other evidence of domestication is abundant (Lu, 1999).

This period of more mesic conditions lasted only about 2000 years, and one might expect that with a gradual return to conditions much like those of the very dry full-glacial, there would also be a return to the high-mobility patterns which characterized that period. Such is not the case, however. The Younger Dryas was unusual, in that it was a climatic episode that was even more sharply bounded and more dramatic than other D/O cycles and was the most volatile period of the last 14.5 ^{14}C ka. As a result, the Late Paleolithic hunter-gatherers of arid western China were faced with a sudden problem in feeding a population that had probably increased significantly during the preceeding millennia, but which had only limited abilities to shift between the high- and low-mobility strategies required by rapid changes in the size and location of large mammals and other high-return resources. What was most consistent was the availability of plants, and we think it was during the Younger Dryas, 11.2–10.1 ^{14}C ka, that the seeds of the agricultural revolution in western China were initially sown. In the relatively few locations where plant resources could produce a viable resource base, such as near springs and the toes of alluvial fans where mountain streams sink into the desert, the actual manipulation of the growth cycle of plants may have started. Compared to the pre-LGM, lithic assemblages are often much larger, more diverse, and sometimes include plant processing equipment, indicating a broad diet. These features are best documented in Pigeon Mountain Basin where surface lithic assemblages at several sites contain a variety of micro- and macrolithic cores, debitage, and tools including microblades, anvils, percussion flaked "Helan Points," pressure-flaked bifaces, a variety of scrapers and gouges, ground celts, and thin grinding stones (Elston *et al.*, 1997; Madsen *et al.*, 1998). A continuing focus on hunting is indicated by the elaboration of microlithic technology, adding a variety of end-hafted, retouched microblades serving as small knives, endscrapers, drills, awls, and arrow points to basic microblade segments functioning as side-mounted insets. The reduced mobility fostered by both this restricted distribution and the additional time required to select and plant favored seeds was likely exacerbated following the Younger Dryas. While the period between ~10 and 9 ^{14}C ka was considerably wetter, a shift away from the seasonal equability that characterized the Younger Dryas resulted in a need for increased winter storage of collected foods, and we think it was then that farming firmly took root as a subsistence strategy. We also think, however, that a portion of the population did manage to make the transition back to high-mobility strategies in some areas. Lu (1998) suggests that sites marked by ceramic and aceramic lithic assemblages in the deserts and steppes of northern China, dating 10–7.0 ^{14}C ka and later, represent foragers and possibly pastoralists. Our own research in the eastern Tengger (Elston *et al.*, 2001; Elston *et al.*, 2005) indicates that foragers operated there through the Middle Holocene. Thus, the Younger Dryas and its immediate aftermath may also have been the periods when the farmer/nomad symbiotic dyad that characterizes the Neolithic and the Holocene worldwide had its start.

This sequence is largely hypothetical, and is based primarily on the application of theoretical models to the relatively unique climatic sequence in arid China, but does have certain testable implications. Among them are:

1. If the initial part of this model is true, then there should be a change in the distribution of Upper Paleolithic sites from a generalized distribution prior to 20 ^{14}C ka to a distribution restricted to the south and east within the margins of the reduced summer monsoon and to areas of more permanent water, primarily larger streams and rivers outside the monsoon zone. Alternatively, there may have been a marked change in mobility strategies.
2. There should also be an increase in the diversity of tools after 20 ^{14}C ka, reflecting the collection and processing of a wider variety of resources. This may include the initial use of ground stone for processing seeds, but with light use indicating short stays. Where preservation is good, floral and faunal remains should include many low-return resource types.
3. Between 13 and 11 ^{14}C ka, there should be a return of increasing numbers of Late Upper Paleolithic foragers to the desert areas of China, north and west of the present summer monsoon boundary. However, rather than a generalized site distribution pattern in lowland areas, as occurred prior to the LGM, sites should be restricted to the margins of shallow desert lakes, particularly stream and river-fed deltas. That is, site distributions should reflect a more patchy environment. With the return of warmer and wetter conditions, the initial widespread colonization of high-elevation areas probably also occurred.
4. Sites dating to 13–11 ^{14}C ka should contain the remains of both high- and low-return resources, indicating a broad-spectrum diet as well as a diverse array of tools used to collect and process them. Ground stone, where present, should include nonportable, but well used, mortars indicating prolonged stays. Lithic materials should reflect intensive reuse, utilization of poor-grade local materials, and the common use of microblades. A focus on small animals and birds as large game populations decreased under hunting pressure should be reflected in a reduction in the size of hunting armatures.
5. After about 11 ^{14}C ka, the distribution of sites should again be limited in arid northwestern China, with most sites dating to this period restricted to areas well within the summer monsoon zones. The few sites outside this zone will be located near permanent springs and rivers and may have indications of prolonged stays and, perhaps as well, indications of the plant manipulation that led to the development of agriculture. Evidence of the use of millet may begin to appear where preservation is good. In less marginal areas, food resources and associated tools may not differ greatly from the preceding period, but site distributions should reflect an even patchier environment.

3.2 A Hypothetical Model of the Foraging Response to Climate Change During the Transition to Millet Agriculture

West central China is one of only five or six areas of the world where agriculture was developed. Yet, the process by which wild millet was domesticated and settled village life on the loess plateau began remains poorly known, particularly compared to rice domestication (e.g., Yan, 1992; Lu, 1999). The earliest known sites associated with millet, such as Dadiwan, Peiligang, Xinle, and Cishan (Lu, 1999; Bettinger *et al.*, this volume), date to ~7–8 ^{14}C yr ka and represent fully settled village life, with pottery, permanent structures, storage features, domesticated animals, and year-round occupation. This suggests that the transitional sites representing the initial domestication of wild foxtail millet (*Setaria italica*) and broomcorn millet (*Panicum miliaceum*), and the shift from full-time foraging to initial sedentism, remain unknown. Understanding where such sites might be found and what this forager to farmer shift might have entailed requires some testable hypotheses which might structure such research. Bettinger *et al.* expand on this hypothesis in Chapter 7, but it is worth exploring briefly here as part of understanding the entire cultural sequence in arid western China.

It is obvious that millet must have been domesticated by pre-Neolithic foragers somewhere within the central China regions of cold, dry climates to which wild millets are adapted (Baltensperger, 1996). The question is where in that region was that most likely to have occurred, and, in turn, where should archeologists begin to look for the earliest millet agriculture? With Bettinger *et al.* (this volume), we think it more likely to have occurred along the margins of where wild millet is naturally distributed, rather than in central areas where production was greatest and most predictable (e.g., Yan, 1992; Lu, 1999). In these central areas, such as the Wei River valley near Dadiwan and from there east in Henan and Hebai provinces, broad-spectrum foragers undoubtedly began to rely heavily on the natural seed production of wild millet and to develop the processing technology that went with this dependence. Yet, within these central areas, there was little incentive to begin to manipulate seed production precisely because natural production was more reliable. At the margins of natural distribution, on the other hand, particularly along the northern and western margins, short- to moderate-term climate change cycles would have had a much more dramatic effect both on where wild millet would grow and on the amount of seed individual patches of millet would produce. Foragers in these areas, as did their cousins to the south, undoubtedly began to utilize wild millet during the Pleistocene/Holocene transition as part of the larger shift to broad-spectrum foraging and generalized seed processing. While this may likely have occurred during climatic cycles immediately following the LGM, it most certainly had taken place by a period immediately after the Younger Dryas (Shi, 1998; Shi, 2001). As a warmer and wetter climatic amelioration expanded the area where wild millet could grow to the north and west, resource patches were enlarged, and seed processing helped prolong stays at any one point and reduce the costs of moving. As colder and dryer conditions returned after $\sim$8 ^{14}C ka, these more northern foragers would have been faced with a choice of returning to a high-mobility strategy in a resource-poor environment or to begin manipulating seed production to help reduce the need to move frequently between increasingly smaller resource patches.

In short, it is most likely that the earliest domestication of wild millet occurred at the northern edge of its modern distribution where the northwestern margin of the Loess Plateau begins to merge into the dunes of the Ordos and Tengger deserts. Foragers there, with a long history of seed collection and processing behind them, likely began to manipulate wild millets when climatic changes shifted the area of distribution to the south and east. This likely occurred $\sim$10–8 ^{14}C ka and involved the development of storage features and domesticated animals, particularly pigs, which were later to characterize full-blown agricultural village life (Pechenkina *et al.*, 2005). This hypothetical model for the domestication of millet is not unlike that proposed by Higham and Lu (1998) for the domestication of rice in the middle Yangtze River valley, in that they also suggest it occurred on the margins of where wild rice now grows and involved a history extending back to at least the LGM.

This hypothesis is rather broad and undoubtedly will require modification as sites earlier than Dadiwan are found, but it does have a number of testable features:

1. Most obviously, the model predicts the earliest sites related to the domestication of millet will occur in a broad arc extending northwest from the juncture of the Wei and Yellow Rivers east of Xian through areas of the Mu Us (Ordos) Desert, turning southwest through Ningxia and into Gansu, and reaching to Lanzhou in the west. Finding of the earliest sites to the south and east of this arc would cast doubt on the model.
2. Within this zone, such sites are likely to be found along permanent streams, perhaps near the confluences with smaller streams in refugia situations where wild millet might still be growing after its extirpation from surrounding areas. Contemporary sites between these refugia are likely to be indistinguishable from earlier foraging sites.
3. These sites should be characterized by abundant foxtail and broomcorn millet seeds, together with the tools to collect and process them, such as abundant cooking vessels. The model would not predict the presence of permanent year-round living and storage structures and other signs of settled village life. These are expected to be temporary foraging sites, perhaps representing prolonged stays, but still part of an overall mobile foraging strategy. Evidence of long-term occupations should exist, but will be in the form of an increased diversity of tools, the use of poorer quality toolstone, and the prolongation of tool use-life.

3.3 The Environmental Impacts of Nomadic Pastoralism on the Deserts of Arid Western China During the Mid-to-Late Holocene

The rapid and dramatic climate change events associated with the onset of each new D/O cycle appear to have had an equally dramatic impact on human foragers during the Holocene. Certainly, biotic communities responded rapidly to such events, with lag times of only 50–200 years (e.g., Viau *et al.*, 2002; Williams *et al.*, 2002; Zhu *et al.*, 2002; Tzedakis, 2005; Chen *et al.*, 2006). Where human foraging is closely linked to the composition, distribution, and density of these communities, cultural change at the level of complex agricultural societies also appears to correlate with the initiation of each cycle (see e.g., deMenocal, 2001; Hodell *et al.*, 2001; Sandweiss *et al.*, 2001). In China, a number of climatic change events during the Mid-to-Late Holocene appear to be related to marked cultural shifts associated with complex agricultural societies (e.g., Wang *et al.*, 1993; Mo, *et al.*, 1996; Huang, 2002; Jin and Liu, 2002; Huang *et al.*, 2003; An *et al.*, 2004; Huang *et al.*, 2004; Wu and Liu, 2004; An *et al.*, 2005). While these are relatively well known, the impacts foragers and pastoralists have had on the process of desertification in western China have been little studied. The assumption is usually that until the advent of intensive agriculture and modern state systems, the relationship between environmental change and cultural change was unidirectional. Based on our work in the Tengger Desert area of western Inner Mongolia, we can suggest a number of testable hypotheses about how pastoralists might have affected the marginal environments of these desert regions.

It is unclear whether subsistence intensification in the terminal Pleistocene–Early Holocene led to agriculture in the Tengger, or when, and in what form, pastoralism arrived there. Without intensive irrigation, the region is too arid and soils too poor to support more than garden horticulture at springs and perennial streams (ALERMP, 2002; Zhou, 2002), so pure farming or farming with village-based herding (Abdi, 2003) may be viable only in the piedmont area on the eastern Tengger margin. Evidence of intensive agriculture (farming tools, substantial structures, storage facilities, deep middens) is so far absent in the region (Madsen *et al.*, 1996; Dematté, 2004). Village-based pastoralism may have started as early as ~7 ^{14}C ka, as small numbers of sheep bones occur in Early Yangshao sites to the south and east and are common by the Middle Neolithic ~6.5 ^{14}C ka (Ren, 1996). Population began to increase among northwestern Loess Plateau farmers about 6.0 Cal ka, accelerating in Majiayou and Qijia (4.0–3.8 Cal ka) times (An *et al.*, 2004). Qijia site numbers spiked in northern Gansu and NE Qinghai south of the Tengger, and the agropastoralist (sheep, cattle) Qijia even expanded above the Great Wall (Fitzgerald-Huber, 1995). An *et al.* (2004) attribute this growth to the warm/dry climate ~7.0–5.0 Cal ka, allowing dryland farming at increasingly higher elevations, but Russell (1988) predicts a greater reliance on herding after all optimal and marginal agricultural lands have been exploited, which was apparently the case on the Loess Plateau south of the Tengger. Tengger survey data (Elston *et al.*, 2001; Elston *et al.*, 2005) suggest increasingly frequent contacts between desert people and outlander farmers to the south and east, with most identified Neolithic sherds dating to 5.4–3.9 Cal ka. Sedentary farmers or agropastoralists likely exerted pressure on any remaining Tengger foragers by occupying former hunting and gathering territory and forcing them into increasingly marginal environments (cf. Barnard, 1992; Kent, 1996).

The agropastoralist Qijia (4.0–3.8 Cal ka) increasingly relied on cattle and sheep, with the latter probably introduced from the west with wheat and other various aspects of nomadic pastoralism through the Hexi corridor along the southern Tengger margin (Barnes, 1993; Anthony, 1998; Flad and Yuan, this volume). Since sheep were already part of the north-central China Neolithic, introduction of western sheep would only make sense with a different variety of animal (perhaps bred more for wool than meat) and probably different herding techniques and technology. In fact, the elements of nomadic pastoralism (grazing animals, carts, portable dwellings, ridden horses, camels, metallurgy, weapons, ritual, ideology) had diffused together across north-central Asia from the western steppes by the Early Bronze Age (4.0 and 3.7 Cal ka) (Barnes, 1993; Fitzgerald-Huber, 1995; Harris, 1996; Anthony, 1998). We are reasonably confident that pastoralism in some form reached the Tengger between ~4.0 and 3.0 Cal ka, and possibly even earlier (Potts, 2004). Whether Tengger foragers adopted pastoralism or were absorbed or displaced by pastoralist incursion is unknown at present. Tethered agropastoralism of the Qijia type seems unlikely on the western side of the Helan Shan because of the lack of arable land there. However, transhumant pastoralism, derived from, or a form of, agropastoralism involving the seasonal movement of herds between summer mountain pastures within range of permanent settlements in the lowlands, seems possible (Abdi, 2003). The western Helan Shan piedmont was probably within the range of people based along the Yellow River, but transhumant sites may be rare at Jilantai, which lies 100 km from the river across desert (Figure 1). If early desert pastoralism was seasonally transhumant (Abdi, 2003), but tethered to permanent water in the dry winter, it is likely to have transformed mountain brushy steppe communities into grassy meadows, decreased abundance of *Nitraria* and *Saxaul* in sandy desert plant communities while increasing other shrubs, and greatly affected wetland communities around lowland springs (ALERMP, 2002). In cold dry intervals, these trends would be intensified.

Nomadic pastoralism involving camels is likely to have had an even greater impact. Archeological Bactrian camel bones in Late Neolithic (~6.0 Cal ka) northern China probably represent wild camels (Tulgat and Schaller, 1992). Bactrian camels were domesticated in north-central Asia 5.0–4.5 Cal ka (Zeuner, 1963; Bulliet, 1975; Tulgat and Schaller, 1992; Kohler-Rollefson, 1996; Han, 2000; Flad *et al.*, this volume) and were in common use in China by the Bronze Age Zhou dynasty (3.1–2.4 Cal ka) (Olsen, 1988). Camels allowed pastoralists to extend their range into more fragile areas to which they had no previous access. This would have had a devastating effect on vegetation, causing the release of sand from stable dunes (ALERMP, 2002). Such impacts would be intensified in cold dry intervals.

The first of these may be related to the collapse of the Qijia Culture ~3.8 Cal ka (Elston *et al.*, 2005), although the nature of camel-based pastoralism is poorly known for this period. Bronze Age Shang (3.6–3.1 Cal ka), Zhou (3.1–2.4 Cal ka), and Shajing (3.0–2.4 Cal ka) pottery occurs in the lake basins of the eastern Tengger (Elston *et al.*, 2001; Elston *et al.*, 2005) and is likely related to camel pastoralism during these periods. The shift to a cold, dry climate between 3.1 and 2.5 ^{14}C ka (e.g., Zhang *et al.*, 2000) had a profound effect on cultures of north-central China, degrading both agricultural and pasture lands (Huang *et al.*, 2002; Huang, 2002; Huang *et al.* 2003; Huang *et al.*, 2004; Wu and Liu, 2004) resulting in large-scale southward movement of nomads and the collapse of the Zhou and Shang dynasties. Consequently, we expect to see severe degradation of wetlands (cf. Thenya, 2001; Hongo and Masikini, 2003) and adjacent sandy desert in the eastern Tengger and similar areas between 3.1 and 2.5 Cal ka. Over the last 2500 years, intense episodes of desertification occurred mainly because of land-use practices during the Western Han period (2.2 and 1.8 Cal ka), the Tang Dynasty (1.37–1.10 Cal ka), and from Ming times to 1976 (Bao *et al.*, 2004; Yang *et al.*, 2004). We expect to find evidence of this desertification extending into areas outside the direct influence of these agricultural states that were occupied by pastoralists who interacted with state-based farming communities.

In sum, there is a commonly made assumption concerning the nature of modern desertification in China that we think may be faulty. The assumption is that, unlike farming and tethered grazing, nomadic pastoralism has little impact on desertification events. If true, there should be little or no difference in desertification events after domestication of the camel allowed nomadic pastoralism to expand into the interior Tengger and similar desert areas of arid western China. We can test this expectation in a number of ways:

1. If camel-based pastoralism altered the use of sandy deserts where camels are now commonly found, there should be a difference in the distribution of pastoralist archeological sites before and after ~4.5 Cal ka. Occupation of the interior and culturally more marginal desert areas should intensify after the introduction of the camel.
2. Goat/sheep-based pastoralism may have had a similar, albeit less obvious, impact on the rates and intensity of desertification events. If so, it should be detectable by making a similar comparison of areas with and without occupation by pastoralists before and after ~8 Cal ka.
3. If camel-based pastoralism has a distinct impact on desertification, then there should be differences in the extent, rate, and intensity of desertification before and after the introduction of the camel. These may be difficult to detect, since there were differences in the intensity of the underlying Holocene climatic cycles (e.g., Chen *et al.*, 2006), but it should be possible to compare desert areas where camel pastoralism did and did not occur to identify the speed with which stabilized dunes began to mobilize, and the degree and rapidity of change in the productivity of vegetation common to sandy deserts.
4. Such change is also likely to be reflected in the intensity of change in isolated wetland oases, since these would have been the focus of occupation during desertification events. While hunting/gathering foragers would also have affected such areas during times of stress, the addition of domesticated animals to the mix would have substantially added to these impacts. As a result, there should be a reduction in the size and productivity of these isolated wetlands during comparable cycles before and after the advent of pastoralism. These changes should be evident in pollen sequences from these wetland areas.

4. Discussion and Summary

Long-term climate cycles on the order of stadial to interstadial periods have long been known to have had a dramatic and readily identifiable effect on prehistoric human societies due, obviously, to the intensity and great length of these Milankovitch cycles. Less obvious has been the relationship between cultural change and climatic cycles of shorter duration. These century- to millennial-scale climate cycles, including 6000 year Bond cycles, 1500 year D/O cycles, and those of even shorter duration, are often initiated by dramatic rapid change events that are reflected in the rapid transformation of biotic communities on which human foragers, early farmer/foragers, and pastoralists depended.

In many areas of the world, there is an increasing understanding of the relationship between prehistoric cultural change and these short-term climate cycles. In China, this is less true due to a traditional focus on the descriptive aspects of archeology and a reduced focus on the how and why of human social change. To help rectify this situation, we here posit a number of theoretically based hypotheses about human/climate dynamics in arid western China over the course of the last ~40,000 years.

First, we speculate that a reduction in the size and productivity of grasslands during the LGM caused Late Upper Paleolithic foragers to add to the pursuit of high-ranked resources a broader spectrum foraging strategy that included the collecting of seed resources. This would have resulted in both a change in mobility and a shift of a generalized occupational pattern to the south and east. Thus, we expect a preponderance of sites dating to this period to be restricted to areas of the reduced summer monsoon and for sites outside this zone to be restricted to areas of permanent streams and springs. Second, this pattern likely intensified during the Younger Dryas, and the manipulation of seed resources probably was established during this short, but intense cold, dry climate cycle. When the shift away from seasonal equability and an increased need for winter storage was added to this plant manipulation during the following period, farming took root in western China. We speculate that limited evidence of plant processing associated with the use of these seed resources should appear during the LGM and become widespread by the Younger Dryas. Flaked stone tools should also reflect an increasing reliance on smaller game and a reduction in mobility. Third, we speculate that millet agriculture developed out of this broad-spectrum foraging base in areas at the northern and western margin of where millet agriculture is now found. We think sites showing the earliest evidence of millet domestication will be found in a broad arc from the northern Ordos Desert west and south to western Gansu. Fourth, we think that nomadic pastoralism, especially that associated with camels, might have had a significant impact on the rate and intensity of desertification during Mid-to-Late Holocene climate cycles. We expect this to be most evident in the central areas of sandy deserts, which these domesticated animals allowed mobile foragers to reach in significant numbers for the first time.

While these hypotheses are likely to be wrong in many details and may prove to be incorrect in some major aspects, we hope that at the very least they and others like them can help guide future archeological research in China. To a large extent, our current understanding of prehistoric cultural change in China is a product of happenstance, with a great many sites that have been excavated having been identified by chance encounters with a farmer's plow or railroad right-of-way stakes. An active search for sites that will help us understand China's past requires some criteria to help guide that search. We think the development of hypotheses grounded in an understanding of the climatic and biotic cycles that underpin cultural change is a step in that direction.

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The transition to agriculture in northwestern China

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Abstract

Agriculture can evolve independently only where intensive hunter-gatherer plant use has previously evolved, and both developments are limited by two major evolutionary constraints: climatic variability and social convention. During the Pleistocene, environmental variability constrained plant productivity and therefore plant-intensive subsistence; but during the Holocene it was the hunter-gatherer social conventions that constrained the evolution of plant-based agricultural subsistence. Specifically, in places with continuous hunter-gatherer occupation (i.e., the Near East), social conventions prohibiting the ownership of land curtailed intensification and prolonged the transition to agriculture. In contrast, northwest China was virtually uninhabited during the Early Holocene. Here, new social orders favoring the ownership of land were free to emerge without restriction, so the transition to agriculture was rapid. Semi-permanent settlements and domesticated broomcorn millet emerged abruptly in the western Loess Plateau at Dadiwan by 7.0 ka with no local hunter-gatherer ancestry. We propose that the intensive plant specialization required for domestication and incipient agriculture emerged first in the desert margins north of the Yellow River and migrated southwards to the more humid and fertile floodplains of the Loess Plateau west of the Liu Pan Mountains, perhaps in response to increasing aridity and climatic instability during the Early Holocene.

1. Introduction

Between 10.1 and 8.1 ka,[1] the hunter-gatherers of north China authored an agricultural revolution that incorporated a wide variety of species but centered on millets (*Setaria italica* and *Panicum miliaceum*), resulting in their domestication. Of the ten or so instances known worldwide in which agriculture is thought to have evolved independently (Richerson *et al.*, 2001; Smith, 2001), this is the least understood and most problematic because it is the only one where this development cannot be traced *in situ* out of a long hunter-gatherer tradition. North China thus runs counter to all other known cases where agriculture developed slowly by hunter-gatherers seeking to enhance the productivity of environments with which they had become intimately familiar over many thousands of years of occupation. In what follows we explore the transition to agriculture as an evolutionary problem and from that perspective detail the presently known archeological record that leads to the Dadiwan complex, the westernmost center of early millet domestication in north China.

2. Agriculture as an Evolutionary Problem

It is useful to introduce the origin of agriculture as an evolutionary problem by means of a metaphorical framework common in evolutionary analysis, outlined here in brief. Two basic factors set the tempo and direction of both organic and cultural evolutions (see Richerson *et al.*, 2005). The first are factors *external* to the evolutionary process itself, most notably changes in the earth's physical and chemical environments, which can determine the direction and speed of evolutionary change. The second are factors *internal* to the evolutionary process, most notably the topography of the adaptive landscape in question – the configuration of its adaptive peaks and the width and depth of the valleys that separate them (e.g., Wright, 1932; Eldredge and Gould, 1972; Boyd and Richerson, 1992). The wider and deeper these valleys are, for example, the longer it will take to develop the innovations or combination of innovations needed to bridge from one local optimum (a "peak" on the "adaptive landscape") to another higher one. The relative importance of these factors is, of course, hotly debated. If the adaptive landscape is unimodal and relatively smooth, evolutionary change will keep time with environmental change, as externalists would have it. If it is convoluted and deeply fissured, evolutionary change may be checked by adaptive valleys and its local contours tracked in a way that has little to do with environmental change, as internalists argue. The development of agriculture is worth thinking in this way because it is so late in time, suggesting that its evolution was strongly checked by some set of external or internal factors. In comparison to the earliest representatives of the genus *Homo*, which appeared 2.5–2.3 million years ago, and the earliest modern humans, which appeared about 150,000 years ago, agriculture is remarkably recent, evolving independently in only a few places (e.g., the Near East and north China) during the Early Holocene, later than that in several others (e.g., Mesoamerica) and in some places not at all (e.g., California, Australia). We contend this trajectory is due to a combination of external and

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[1] *ka* refers to radiocarbon years, unless otherwise specified.

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internal factors whose relative importance varied through time. Internal factors alone are sufficient to explain the absence of agriculture before about 80,000 years ago. Premodern *Homo* clearly lacked the requisite intellectual and technical capabilities, and the anatomically modern humans of the last interglacial (130,000–80,000 years ago) were uniformly archaic in behavior, i.e., not behaviorally modern, and likely also neither cognitively nor culturally capable of developing agriculture. After this, between 80,000 and 10,000 years ago, external factors were more important. During most of this time, and certainly by about 40,000 years ago, humans were intellectually and technically capable of developing agriculture, but Pleistocene climate and environment, in combination with the special requirements of intensive plant use and agriculture (i.e., costly preparation, harvesting and processing), prevented them from doing so. With climatic amelioration after 10,000 years ago internal factors again became dominant, this time centering on the difficulty of evolving social arrangements suitable to agriculture. Here, we are concerned first with the period 80,000–10,000 years ago, when the evolution of intensive plant-based subsistence was limited by climate; and second, with the period after 10,000 years ago, when the intensive use of plant products and ultimately the development of agriculture was limited by social organization.

2.1 Pleistocene Climate Made Intensive Plant Use Impossible

During the last glacial, atmospheric levels of CO_2 were low, climate was very dry over large areas and probably, most important, climates were characterized by high-amplitude fluctuations on time scales of a decade or less to a millennium. Because subsistence systems specialized on plant resources are vulnerable to weather extremes and because they evolve relatively slowly (>1000 years), intensive plant-based agricultural systems could not evolve during the Pleistocene. The following discussion draws heavily on our earlier work on this subject (Richerson *et al.*, 2001), which is more detailed here than space permits.

Ice age climates varied at very short time scales. Ice core data show that during the last glacial, climate was highly variable on time scales of centuries to millennia (Dansgaard *et al.*, 1993; Ditlevsen *et al.*, 1996; Clark *et al.*, 1999; GRIP 1993). Figure 1 shows data from the GRIP Greenland core.

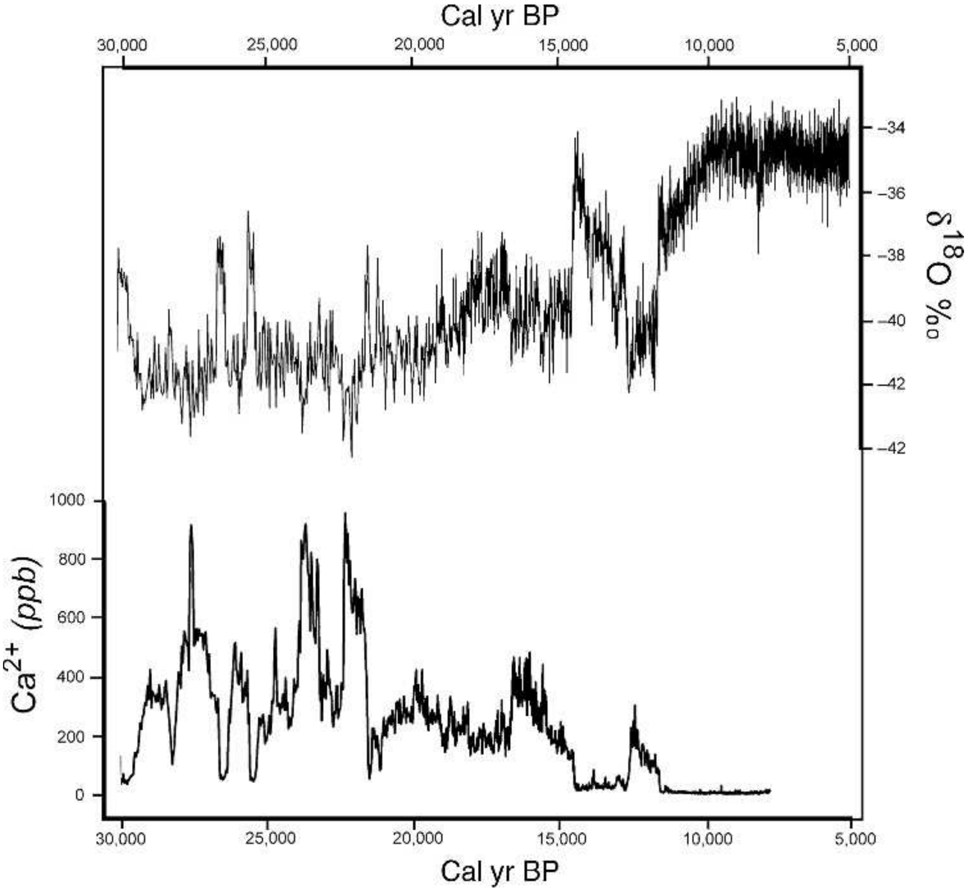

Fig. 1. Late Pleistocene–Early Holocene climate change. The upper curve represents $\Delta^{18}O$ fluctations, a generalized proxy for temperature and humidity (GRIP Members, 1993; Dansgaard et al., 1993). The lower curve plots changes in Ca^{2+} deposited in Greenland ice, a proxy for aridity and hemispheric dust transport (Fuhrer et al., 1999).

The $\delta^{18}O$ curve is a proxy for temperature; less negative values are warmer. The Ca^{2+} curve measures dust concentrations, a proxy for dust-producing arid climates. Together they show that the last glacial period was arid and extremely variable compared to the Holocene. There are sharp millennial-scale excursions in estimated temperature, atmospheric dust and greenhouse gases, right down to the limits of the high-resolution records of the ice core data. The highest resolution Greenland ice records show that millennial-scale warming and cooling events often began and ended very abruptly and were often punctuated by quite large spikes of relative warmth and cold with durations of a decade or two (e.g., von Grafenstein *et al.*, 1999). By the standards of the last glacial, the Holocene (the last relatively warm, ice-free 11,600 years) has been a period of very stable climate.

The dramatic climate fluctuations of the Pleistocene are also registered at lower latitudes. Hendy and Kennett (2000) report water temperature proxies from sediment cores from the Santa Barbara Basin, just offshore of central California, that show millennial- and sub-millennial-scale temperature fluctuations with an amplitude of about 8° C from 60 to 18 thousand years ago, compared to fluctuations of about 2° C in the Holocene. These millennial-scale events often show very abrupt onsets and terminations and are often punctuated by brief warm and cold spikes, as in the Greenland cores. Schulz *et al.* (1998) analyzed concentrations of organic matter in Arabian Sea sediment cores that show variation attesting to sharp changes in the strength of the Arabian Sea monsoon over the past 110,000 years. As with the data from Santa Barbara, the climate proxy variation in the upper part of this Arabian Sea record is well controlled by AMS ^{14}C dating and easily fits the Greenland ice millennial-scale interstadial – stadial oscillations. Furthermore, in southern Italy, Allen *et al.* (2000) have documented changes in the proportion of woody taxa in pollen profiles from Lago Grande di Monticchio that are dominated by large amplitude changes at the century scale and display millennial-scale variations that correlate with the Greenland record. Petersen *et al.* (2000) show that proxies for the tropical Atlantic hydrologic cycle have a strong millennial-scale signal that likewise closely matches the Greenland pattern. Finally, the ultimate Younger Dryas millennial-scale cold episode 12,900–11,600 Cal yr BP, so strongly expressed in the high-latitude ice core records, is reported in proxy records from all over the world, including southern Germany (von Grafenstein *et al.*, 1999), the Cariaco Basin, Venezuela (Werne *et al.*, 2000), New Zealand (Newnham and Lowe, 2000) and California (West 2001). As Cronin (1999, pp. 202–221) notes, the Younger Dryas is frequently detected in a diverse array of climate proxies from all latitudes in the Northern Hemisphere. In the Southern Hemisphere, however, proxy data often do not show a cold Younger Dryas period, although some show a similar Antarctic Cold Reversal just antedating the Northern Hemisphere Younger Dryas (Bennett *et al.*, 2000).

Other records show millennial-scale climate fluctuations during the last glacial that cannot be convincingly correlated with the Greenland ice record. Cronin (1999, pp. 221–236) reviewed records from the deep tropical Atlantic, Western North America, Florida, China and New Zealand. Recent notable additions to this list include Southern Africa (Shi *et al.*, 2000), the American Midwest (Dorale *et al.*, 1998), the Himalayas (Richards *et al.*, 2000) and northeastern Brazil (Behling *et al.*, 2000). Clapperton (2000) details millennial-scale glacial advances and retreats from most of the American cordillera – Alaska and western North America through tropical America to the Southern Andes.

Plant productivity was also limited by lower atmospheric CO_2 during the last glacial. The CO_2 content of the atmosphere was about 190 ppm during the last glacial, compared to about 250 ppm at the beginning of the Holocene (Fig. 2). Photosynthesis on earth is CO_2 limited over this range of variation (Sage 1995; Cowling and Sykes 1999). Fossil leaves from the last glacial have higher stomatal density, a feature that allows the higher rates of gas exchange needed to acquire CO_2 under more limiting conditions, but also causes higher transpiration water losses per unit CO_2 fixed, exacerbating the aridity characteristic of glacial times (Beerling and

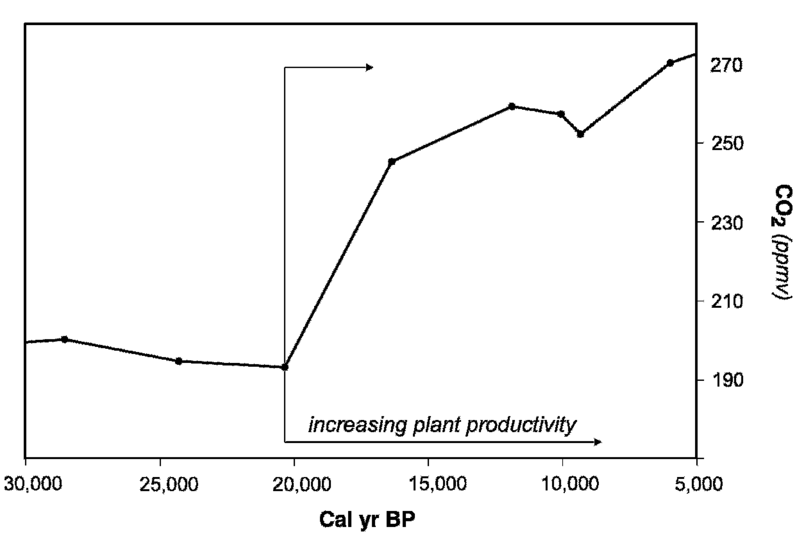

Fig. 2. Late Pleistocene–Early Holocene increases in atmospheric CO_2 as recorded from Antarctic ice (Barnola et al., 1987).

Woodward, 1993; see also Beerling *et al.*, 1993). Beerling (1999) estimates the total organic carbon stored on land as a result of photosynthesis was either 33% or 60% lower at the Last Glacial Maximum than in the Holocene, depending on the model used. This low mean productivity, along with the climatically induced greater variance in productivity, would have greatly decreased both the efficiency and reliability of plant-based subsistence during the last glacial. In short, the force of Pleistocene selection favored the evolution of human behaviors associated with animal hunting but not those geared toward the use of plants. Evolution of the former was therefore rapid and varied, that of the latter more static and limited.

2.1.1 Impacts on the Evolution of Intensive Plant Use and Agriculture

High-frequency climate and weather variation would have made the development of intensive plant exploitation extremely difficult, and agriculture virtually impossible. Holocene millennial-scale variation was subdued in comparison to events of similar duration during the last glacial, yet it significantly affected agricultural production (Lamb 1977). Extreme years during the Little Ice Age (400–150 Cal yr BP), for example, caused notable famines (Grove, 1988). Such extremes would have been more exaggerated and frequent during last glacial times. If high-frequency climate variation at lower latitudes was roughly as great as in Greenland, an hypothetical last glacial farming system would face crippling losses in more years than not. Devastating floods, droughts, windstorms and other environmental calamities, now experienced once a century, might have occurred once a decade. Few years would be suitable for good growth of any given plant population. It is difficult to imagine intensive plant use and agriculture evolving under these conditions. Even under relatively benign Holocene conditions, intensive plant collectors and agriculturalists often barely eke by using sophisticated risk-management strategies for coping with yield variation (Winterhalder and Goland, 1997). They find storage an excellent means of meeting seasonal shortfalls, but not of coping with interannual risk, much less multi-year shortfalls (Belovsky, 1987, p. 60).

In regions that might have escaped the decadal scale variation, detected in the few truly high-resolution climate proxy records available, the evolution of sophisticated intensive plant use would still have been handicapped by the millennial-scale variation universally evident in lower-resolution records. Plant and animal populations can respond to climatic change by dramatically shifting their ranges, but late glacial climate change occurred on time scales too short for the necessary range shifts to occur. As a result, last glacial natural communities must have always been in the process of chaotic reorganization, climate varying too rapidly for communities to reach equilibrium. Pollen records from the Mediterranean and California show just how much more dynamic plant communities were during the last glacial than in the Holocene (Heusser, 1995; Allen *et al.*, 1999).

Opportunism was probably the most important strategy for managing the risks associated with plant food use during the last glacial. Seed dormancy in annual plants spreads their risk of failure over many years, and perennials vary seed output or storage organ size substantially between years as weather dictates. In a highly variable climate, the specialization of one or a few especially promising species would be highly unlikely, because "promise" in one year or even for a decade or two would run afoul of streaks of years with little or no success. By contrast, most years are favorable for at least some species, so generalized plant exploitation systems are compatible with highly variable climates. The acorn-reliant hunter-gatherers of California, for example, used several kinds of oak, gathering less-favored species when more-favored ones failed (Baumhoff, 1963, Table 2). This worked because the annual production of individual trees is highly variable from year to year and correlated within species but independent among different species (Koenig *et al.*, 1994). Pleistocene hunter-gatherer systems would have been even more diversified, lacking the kind of commitment to a single-resource category (such as acorns) observed in California.

The evolution of intensive plant use and agriculture is limited by internal factors that magnified the effect of short-term late glacial climate change. It is unlikely that intensive plant exploitation systems could have tracked intense millennial- and submillennial-scale climatic variation because plant-dependent human diets do not develop that rapidly. A safe, balanced plant-rich diet takes time to evolve because plant foods are generally low in protein and often high in toxins. Other changes are required as well. Seasonal rounds have to be modified and women's customary activities given more prominence relative to men's hunting. Whether borrowed or evolved *in situ*, these changes tend to be slow (North and Thomas, 1973; Bettinger and Baumhoff, 1982). It is unlikely that even the sophisticated hunter-gatherers of the last glacial would have been able to solve the complex nutritional and behavioral problems associated with a plant-rich diet while coping with unpredictable, high-amplitude climate change on time scales shorter than the equilibration time of plant migrations – shorter, indeed, than actual Holocene trajectories of plant intensification leading to agriculture. As for the record, the direct archeological evidence suggests that intensive use of the technologies that underpinned agriculture post-dates 15,000 years before present (Bettinger, 2001).

Finally, there is the effect of lower average rainfall and carbon dioxide during the last glacial. This reduced the area of the earth's surface suitable for intensive plant use and agriculture (Beerling, 1999) and thus reduced the probability of developing adaptations based on these in a given unit of time. The key effect here was on cultural transmission. Henrich (2004) argues that the ability to maintain complex cultural behaviors varies exponentially with group size, specifically the number of individuals exchanging cultural information. This means that the rate of cultural evolution will be more rapid when beneficial innovations and complex behaviors are maintained by large, interacting groups.

Therefore, the late glacial reduction in the areas suitable for intensive plant use and agriculture, and the isolation of these areas from one another, would have reduced effective group size and increased chance losses of beneficial innovations and complex behaviors, slowing the rate at which intensive plant use and agriculture could evolve. The slowest observed rates of intensification in the Holocene (e.g., California, Argentina, Australia) failed to result in agriculture until European invasion, i.e., during an interval of just under 10,000 years. Since the fastest observed rate (e.g., Near East and north China) is about 1000 years, a coarse estimate would be that it takes something like 1000–10,000 years for agriculture to evolve under Holocene conditions. For reasons just discussed, with the reduction in areas suited to intensive plant use and agriculture, the rate would have been slower during the last glacial. This would have prevented the rapid adaptation of intensive strategies and the development of agriculture in any favorable locales or during periods that might have existed during the last glacial. Put simply, during the Pleistocene, intensive plant use and agriculture evolving on time scales greater than a millennium could not have kept pace with climate changing on millennial and sub-millennial time scales. Intensive, plant-based subsistence including, but not limited to, the harvesting, processing and cultivation of small-seeded annual grasses such as wheat, barley, maize, rice and millet was therefore impossible until the end of the Pleistocene.

2.2 Agriculture Was Problematic During the Holocene

Holocene climatic amelioration – the combination of CO_2 enrichment, increased moisture and climatic stability – in large part removed the external factors that prevented agriculture during the Pleistocene, leaving it to evolve at a pace set by internal factors: the fissures and peaks that together define the adaptive landscape that has to be negotiated for agriculture to evolve. We have already mentioned that, in the presence of fast-paced late glacial climate change, the fissures on this landscape connected with finding the requisite suite of plants, settlement pattern, work habits, socio-political organization, etc., slowed this evolution enough to prevent the leap from generalized to plant-specialized hunting and gathering, and subsequently to agriculture. Climatic amelioration did not remove these fissures, it merely reduced the time needed to negotiate them down to something like 1000 to 10,000 years – which is not inconsiderable. We strongly suspect that technical barriers – finding productive plants and the means to process them – were the least problematic in this regard; the remarkable sophistication of ethnographic hunter-gatherers in dealing with plants suggests that the necessary technology and knowledge could develop and spread quite quickly. Developing the necessary social and political organization, on the other hand, was much more problematic. In our view, this is the principal contributor to the 1000 to 10,000 years that were required for agriculture to develop. In the remainder of this paper we detail this argument and relate it to the development of agriculture in the Dadiwan area.

2.2.1 Low-Level Food Producers

Smith (2001) has thoughtfully detailed the spectrum of views about the difference between hunter-gatherers and agriculturalists and the pace – fast or slow – at which agriculture evolved to replace hunting and gathering following the first experiments with food production. His concern with nomenclature is well placed and solidly grounded in a notion of process. By interposing a category of "low-level food producer" between the traditionally recognized categories of "hunter-gatherer" and "agriculturalist," Smith is not merely arguing that the transition from hunting and gathering to agriculture was sometimes slow, that groups identified as hunter-gatherers sometimes engage in a little food production and that agriculturalists sometimes fall back on hunting and gathering when their crops fail – these unremarkable facts have long been known. Rather, he is asserting that the transition to agriculture is governed by a suite of relationships that make low-level food producers *qualitatively* different from hunter-gatherers on the one hand, and full-time agriculturalists on the other (Smith, 2001, p. 33). Smith does not elaborate on these relationships but offers some important clues, firstly, that the temporal persistence of low-level food production (typically over several millennia) suggests systems internally configured in ways that promoted stability (Smith, 2001, p. 25) and, secondly, that these systems are perhaps most reliably distinguished from systems of food procurement (hunting and gathering) by the presence of land ownership (Smith, 2001, p. 32). Smith does not overtly link these two features but there is a sensible connection on the face of it. Specifically, it is plausible that the assurance provided by land ownership might promote the stability that is said to characterize nascent food-producing systems and increase the incentive for individuals to experiment with food production, an equation that would root the origin of food production in the prior development of land ownership. Smith avoids this equation and there are problems with it.

Land ownership does not empirically segregate low-level food producers from hunter-gatherers cleanly enough to make the case open and shut. The generalization may hold for the hunter-gatherers of Eurasia and Africa, but not those of North America, who constitute the bulk of the ethnographically recorded hunter-gatherers living in non-marginal environments, many of whom were land owners. Virtually all the hunter-gatherers of cismontane California, for example, owned and defended land but few, if any, engaged in food production in the usual sense, i.e., with planting or sowing. Of the seven central Great Basin hunter-gatherer groups that burned plots and sowed them with wild seeds, six claimed those plots as family property only temporarily (Steward, 1941, pp. 281, 314) – in keeping with the Shoshoni principle that property rights extend only to things on which work has been done (Steward, 1938, pp. 106, 253). These use rights were identical to those enjoyed by a Shoshoni couple who, because they built the house in which they lived, owned the ground on which it sat only so long as they continued to live in it. Among the groups that sowed, only the Reese River Shoshoni observed more stable, band-level, proprietary use rights – to pine nut groves and possibly wild seed plots (Steward, 1941, p. 314) – of the kind that might be seen as encouraging such experiments. The Owens Valley Paiute, on the other hand, who extended such band-level use rights even more generally – to pinyon groves, hunting and fishing territories, wild and irrigated seed plots – did not undertake experiments with reseeding (Steward, 1930; Steward, 1938, p. 53). On the face of these data, landholding is insufficient to account for food production, although it must surely promote it.

Still on the matter of the ethnographic record, it is further troubling that low-level food producers are so poorly represented in comparison to groups that make either almost all or almost none of their living by agriculture (i.e., agriculturalists and hunter-gatherers). This makes it possible to argue that the mixed economy of low-level food production is inherently unstable, or simply unattractive, relative to the pure economies of either agriculture or hunting and gathering (Hunn and Williams, 1982). The aforementioned temporal persistence of low-level food production in the archeological record leads Smith to discount this evident gap as an artifact of time and history. He sees in the gap the cumulative effects of agricultural expansion and the very slow gravitation of low-level food producers toward more intensive forms of agriculture throughout the Holocene, which left very few in the "middle ground." Agricultural holdings certainly expanded during the Holocene, but the considerable number of ethnographic North American hunter-gatherers dwelling in formerly agricultural lands (e.g., Southern Paiute, Apache, Cheyenne), betrays a surprising degree of agricultural retrenchment that swelled the ranks of hunter-gatherers without adding materially to the middle ground. Under the host of pressures that increasingly squeezed systems of all kinds as the Holocene went on, low-level food producers fared far less well than either agriculturalists or hunter-gatherers. On the whole, the ethnographic proportion of low-level food producers relative to hunter-gatherers and agriculturalists (i.e., low-level food producers: hunter-gatherers + agriculturalists) is commensurate with Belovsky's (Fig. 9 in Belovsky 1987) energetic map of the range of conditions (cropping rates against biomass productivity) over which each is favored. Low-level food production, as identified by both Smith and Belovsky, occupies only a sliver of the ethnographic record. The post-Pleistocene reshuffling of global environment, however, stabilized only in the Late Holocene. It is quite possible that the conditions Belovsky thinks would have promoted low-level food production were more characteristic of Early and Middle Holocene environments and that the absence of ethnographic low-level food producers is an artifact of Late Holocene environments.

The strongest empirical counter to the argument that low-level food production is unstable or narrowly attractive is archeological – the observed longevity of low-level food production in individual regional sequences. As Smith notes, the interval between the initial appearance of (low level) food production and the appearance of full blown agriculture, as denoted by settlement–subsistence systems centered around food production, is perhaps 5500 years in Mesoamerica, 4000 years in eastern North America and (arguably) 3000 years in the Near East. Longevity, however, is also a characteristic of unstable systems. As we have seen, the remarkable temporal persistence of Pleistocene hunting and gathering can be laid to an unstable environment that frustrated the perfection of technologies, behaviors and subsistence intensification needed to set the stage for food production (Richerson *et al*., 2001). Even where climate is stable, hunter-gatherer populations and the resources upon which they depend, hence their subsistence behaviors, are not. Human and resource populations are constantly in change, rising or falling inversely with each other, with subsistence behavior following suit, in roughly century-long cycles (Belovsky, 1988; Winterhalder *et al*., 1988). In brief, the feedback between population and resources means that resources will be most abundant when human population densities are lowest and will then drop as human population grows in response to this abundance, until the human population drops in response to declining resource abundance, allowing resources to rebound. The system as a whole (humans + resources + subsistence patterns) may be dynamically stable and therefore temporally persistent. If so, it is because along the way its hunter-gatherers have continually faced and successfully responded to the dramatic cycling between extremes of resource abundance and scarcity by making major changes in subsistence, settlement and, almost surely, socio-political organization (see Barton *et al*., this volume). It is reasonable to think that the dynamics of low-level food production would have been broadly similar, alternately appearing and disappearing in response to this and other sources of instability.

In the most plausible scenario, the stable limit cycle regulating the relationship between population and resources causes low-level food production to appear when diet breadth expands during phases of resource depression and to disappear when diet breadth contracts during ensuing phases of resource abundance, going full-round every century or so (Belovsky, 1988, p. 351; Flannery, 1973; Winterhalder and Goland, 1993). Since the maintenance of cultural behaviors is contingent on group size (Henrich, 2004), this fluctuation in population would independently reinforce the effect of diet breadth in periodically eliminating food production from the behavioral repertoire, because population (hence, the prospect for cultural transmission) falls to its lowest when diet breadth is narrowest and least favorable to food production. Such a system might well be dynamically stable, and thus temporally persistent, but not low-level food production itself, which would phase in and out. The limits of archeological resolution are of major concern in this regard. If archeology cannot resolve the two phases of this cycle, at most a half-century apart, low-level food production might appear to be continuous and, by extension, stable, when it is actually discontinuous and unstable.

A system that included low-level food production but consistently cycled through a phase of pure hunting and gathering would obviously retard the development of reproductively challenged cultivars (e.g., with non-shattering rachises), because they would tend to disappear each time cultivation ceased. If, however, the compromising traits were under relatively simple genetic control that responded quickly to selective cultural modification (e.g., tough rachis wheat responding to harvest selection; Harlan, 1967), it might repeatedly develop at least often enough to appear archeologically continuous. More complex traits might actually manage to persist continuously if they were not so severely handicapped that selection removed them altogether from the landscape during the hunter-gatherer phase of the cycle. In both these cases, however, the periodic abandonment of cultivars would ultimately limit the development of traits that were beneficial to humans under cultivation but deleterious to the plants themselves when left to fend on their own in the wild. On the other hand, if population densities were high enough, and local groups within a region did not cycle in phase, even cultivars with highly deleterious traits might well develop and persist continuously by passing from group to group as demanded by resource depression.

For those archeologically long-lived systems of low-level food production that suggest continuous propagation of cultivars under complex genetic control (e.g., maize), this last arrangement – some sort of regional interaction sphere involving many local systems – comes closest to reconciling Smith's notion of low-level food production with the stable limit cycles that characterize any individual local system that is heavily committed to wild plants and animals. Unfortunately, this regional scenario brings us right back to where we started. Because regionally maintained cultivars are not subject to the stable limit cycles affecting local systems, their development is no more limited (hence slow moving, i.e., stable), and arguably less limited, than cultivars continuously propagated by a single local system not subject to stable limit reversals. It is unclear in either setting what prevents continual cultivar improvement, leading to an increasing investment in food production via the feedback process described long ago by Flannery (1968). Cultivar resistance to modification is one answer. However, under continual manipulation, even at moderate levels, early cultivars should have accumulated the most critical trait changes (increased seed size, durable inflorescence, etc.) they eventually developed in much shorter order than is observed. Because of this it is possible to argue that cultivar improvement was not retarded by cultivar intransigence but rather by circumstances that determined the rewards associated with their cultivation. It is in this connection that land ownership finally seems salient, firstly, because (as noted at the outset) land ownership seems critical to agricultural investment and, secondly, because land ownership and rules of private ownership in general evolve only with great difficulty and are thus likely to display the slow and uneven pattern of development said to characterize low-level food production.

2.2.2 Social Barriers to Intensive Plant Use

As one of us has outlined elsewhere (Bettinger, 1999a; Bettinger, 1999b; Bettinger, 2001), the greatest challenge to hunter-gatherer resource intensification is not technological but social – the development of rules of ownership that provide individuals the incentive to increase procurement effort. Simply put, where resources are common (i.e., public) property, individuals have little incentive to intensify their procurement effort, the proceeds from which must be split equally with others, whether or not they have invested similar levels of effort. The Hadza of Tanzania provide an apt ethnographic illustration. They have the technology to preserve meat by drying it but seldom do so, since, "To preserve and store it would be largely wasted effort, other people would simply demand meat when their own was finished and it would be wrong to refuse them" (Woodburn, 1968, p. 53). This is likely why resource storage appears relatively late in time, far later than it should have given its technical simplicity and obvious advantages. If stored resources are public resources, the rational individual should never contribute more than the average level of effort, and preferably as little effort as possible. The proprietary use (ownership) of land is even more problematic. Ownership of stored resources is tangibly justified by the labor expended in their accumulation, as Steward (1938, p. 253) observes. Ownership of land, on the other hand, is only justified by labor previously expended – the cost of which has already been paid in full, or by labor to be expended in the future – which others may be equally or even more willing to expend. Conflict, the making of public property into private property by possession and defense (e.g., Rosenberg, 1998), provides only a short-term, unstable solution. A family of fiercely defensive individuals may temporarily succeed in taking and holding land, but if population densities are relatively high and relatively mobile, and neighboring villagers regard land as public property, the land will usually revert to the public domain by force or neglect (see below).

Whatever the good (seed cache, acorn grove, hunting territory or agricultural plot), a stable system of its ownership requires a combination of owner payoffs that are large enough and a large proportion of individuals who acknowledge the right of others to own. The two are related because the benefits of ownership increase as the number of individuals acknowledging ownership rights increases (and the number individuals unwilling to acknowledge ownership commensurately decreases), diminishing the cost of splitting or defending the good. Because the costs of sharing and defense are extremely large when ownership is rare, a well-entrenched public goods system is quite stable. It is not susceptible to overthrow by individuals experimenting one at a time with ownership in groups whose other members find hoarding sinful. It can, however, be replaced via the group-level process described by Soltis *et al.* (1995). If ownership is a group behavior (say of a lineage or group of related lineages forming a coherent socio-political unit) and owning groups fare better than non-owning groups, non-owning groups will gradually be replaced. Since selection here acts on groups rather than individuals, the process is exceedingly slow in comparison to behavioral change driven mainly by individual rational choice, as in the spread of the horse in North America and snowmobiles in the Arctic. Group selection leading to the general practice of land ownership is unlikely to act, however, until hunting and, in particular, gathering practices become so coordinated in tune with local conditions that outsiders moving to a new area cannot get along without local instruction, forcing them to acquire the conventions that promote ownership as part of the mix (e.g., the obligation to punish poachers; McElreath *et al.*, 2003).

The importance of such local conventions is illustrated in Fig. 3, which plots payoffs for landholders and poachers in the absence of poacher punishment (Fig. 3a), and when punishment is present (Fig. 3b). In Fig. 3a, landholder and poacher payoffs both increase with the number of landholders. As landholders increase, the number of poachers decreases, making landholding more profitable. However, the poacher payoff also increases because there is more to poach, reaching a maximum when there is only one poacher and everyone else is a landholder. Poaching is always superior to landholding, but if there are enough landholders (here more than X), the landholder payoff is greater than landholders would obtain if all of them abandoned landholding and reverted to poaching. In this sense, landholding becomes "viable." The circulation of population from locality to locality makes this landholder solution temporary and unstable; poachers would move from localities where poaching is common, and payoffs are low, to localities where landholders are common, and payoffs are high, until poaching became universal. In Fig. 3b, however, poachers are punished by landholders. Where landholders are few, punishment has a negligible effect on the poacher in comparison to its cost to the landholder; as landholding becomes more common the situation reverses because there are more punishers and fewer to punish. At some point, the poacher payoff falls below the landholder payoff. If there are any more landholders than this, landholding is favored; with any less, poaching is favored. In short, if local conventions make poaching less profitable than landholding when landholding is common, and these conventions are learned by newcomers, there will be two kinds of stable communities, landholding and poaching, and group selection will determine their differential persistence according to the disparity in their payoffs.

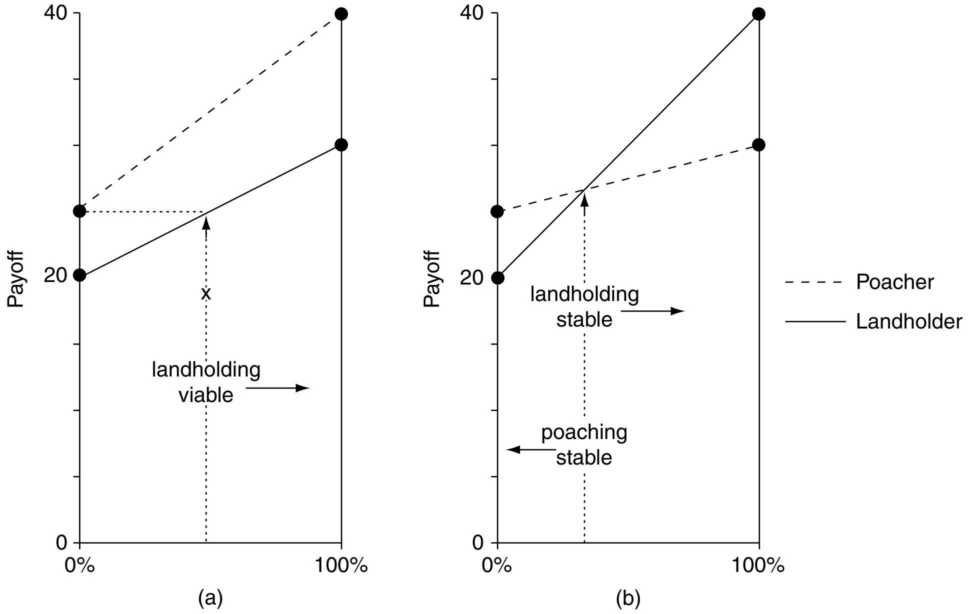

Fig. 3. Payoff structure for "landholders" and "poachers". In 3a, social conventions against poaching do not exist. Here, payoffs for individual poachers always exceed those of landholders. Landholding becomes viable (at "X"), and becomes more profitable as the ratio of landholders to poachers increases. In 3b, the poaching payoff is weakened by punishments issued by the landholders. When landholders are few, poaching pays as the threat of punishment is minimal. However, as the proportion of landholders increases (from left to right on the x-axis), their payoffs also increase. This occurs because the total costs to the landholders for punishing non-landholders decreases in concert with the number of poachers. When social conventions, including punishments designed to maintain group-beneficial behavior evolve via group selection, land ownership becomes a viable and stable strategy.

We strongly suspect that this sort of group selection ultimately accounts for the temporal persistence of low-level food production in many archeological records around the globe. It seems likely that the simplest form of food production, reseeding with wild strains, would have readily developed in the Early Holocene among isolated groups who brought it into play periodically, and that the more complex, productive, and selectively compromised cultivars were subsequently maintained by the same kind of groups interacting on a regional scale. The further development of these regional systems and their cultivars, however, required social conventions governing the use of land, which proceeded through the slow group selection process just described. In this way, hunter-gatherer population growth associated with Early Holocene climatic amelioration would have thwarted agricultural development, prolonging the pattern Smith has labeled as low-level food production.

The limits on agricultural development would obviously be greatest in landscapes that had been occupied and filled by increasingly sophisticated hunter-gatherers for thousands of years well back into the Pleistocene, before any form of food production began. By contrast, the greatest potential for a rapid transition to agriculture would have been in places without long Pleistocene hunter-gatherer histories. In an empty landscape, colonizing groups of low-level food producers might establish proprietary land use practices that encouraged agricultural investment without having to contest these practices with an existing hunter-gatherer population that regarded all land as public domain. Here, the processes of colonization and rapid growth, rather than group selection, would apply. Such situations, however, are rare because the places most favorable to food production are almost always the places most favorable to hunting and gathering in general, and intensive hunting and gathering in particular. Nevertheless, this appears to be the case in north China.

3. Late Pleistocene – Early Holocene Prehistory of North China

The archeology of the Late Pleistocene and Early Holocene is less well documented in north China than in the Near East, Mesoamerica or South America, but is not the mystery it was just two decades ago, when the late K.C. Chang's (1986) final treatment of ancient China appeared. Since then, one of the most significant published contributions available to western scholars has been the synthetic treatment of hunter-gatherer and early agricultural sites, assemblages and radiocarbon dates compiled by Lu (1999). Her work underscored the importance of bridging the temporal gap that has long frustrated attempts to establish a convincing link between the youngest known Late Pleistocene Paleolithic assemblages and the oldest known Middle Neolithic examples of early millet agriculture, traditionally divided into three geographical complexes: Peiligang, Cishan and Dadiwan (An, 1988; Fig. 1; 1991). More recently, other roughly contemporaneous, early agricultural complexes have been identified at Houli, along the eastern-most reaches of the Yellow River, and at Xinle and Xinglongwa in northeast China (Guo, 1995; Underhill, 1997; Yan, 1999; Shelach, 2000). General outlines of Chinese culture history classify these early agricultural complexes as "Middle Neolithic," reserving the "Early Neolithic" designation for a suspected, but largely unidentified transitional period between foraging and farming (Cohen, 1998; Yan, 1999; Cohen, 2002).

The material evidence used to justify the "agricultural" classification of specific sites varies widely. In some cases, the designation is based on the presence of domesticated plant or animal taxa; in others, it is based simply on the presence of ceramics or architectural features that resemble those found at sites with known domesticates (see Lu, 1999). Recent efforts have focused on establishing the degree of agricultural subsistence in Middle and Late Neolithic China on the basis of stable isotope chemistry (Zhang *et al.*, 2003; Pechenkina *et al.*, 2005) and skeletal biometry and paleopathology (Jackes and Gao, 1994; Smith, 2005). At this point, archeological evaluations of the degree or intensity of agricultural subsistence during the Neolithic are just beginning in China. However, with few exceptions, the Middle Neolithic culture areas of north China are viewed as sedentary or semi-sedentary agricultural complexes with domesticated plants and animals along with other markers of intensive plant use such as pottery and ground-stone. None are considered strictly hunters and gatherers.

The first two classically Middle Neolithic complexes of north China, Peiligang and Cishan, are lowland centers (<650 m.a.s.l.), sitting on the middle reach of the Yellow River. Together with Houli, they are often seen as being connected to Late Pleistocene lithic assemblages 200–300 km to the east (e.g., Xiachuan and Xueguan; Chen, 1984; Chen and Olsen, 1990; Lu 1999) or Early Holocene sites 300–500 km to the north (e.g., Nanzhuangtou; Guo and Li, 2002). Noting the co-occurrence of millet and rice remains at Jiahu, a site belonging to the Peiligang cultural horizon, some authors propose that millet domestication is an outgrowth of earlier, rice-centered agricultural systems that originate well south of the Yellow River drainage (Cohen, 2002; Bellwood, 2005). While this remains an attractive, tentative hypothesis for the origin of millet-based agricultural systems located along the middle reaches of the Yellow River and the north China Plain, it does little to explain the near synchronous appearance of millet-based systems at Dadiwan (700–800 km northwest of Jiahu) or at Xinle and perhaps Xinglongwa (1200–1300 km to the northeast).

In contrast to the lowland agricultural centers of the central and eastern Yellow River drainage, Dadiwan is an upland center, on the upper Wei River in the southwestern Loess Plateau (CPAM 1981; CPAM 1982; Zhang and Zhou, 1985). The Dadiwan-type site, the oldest of the complex (sometimes termed Laoguantai), sits at an elevation of about 1800 masl, on the uppermost Wei, more than 700 km west of Peiligang and Cishan.

The difference in elevation and their geographical separation makes it improbable that the Dadiwan complex

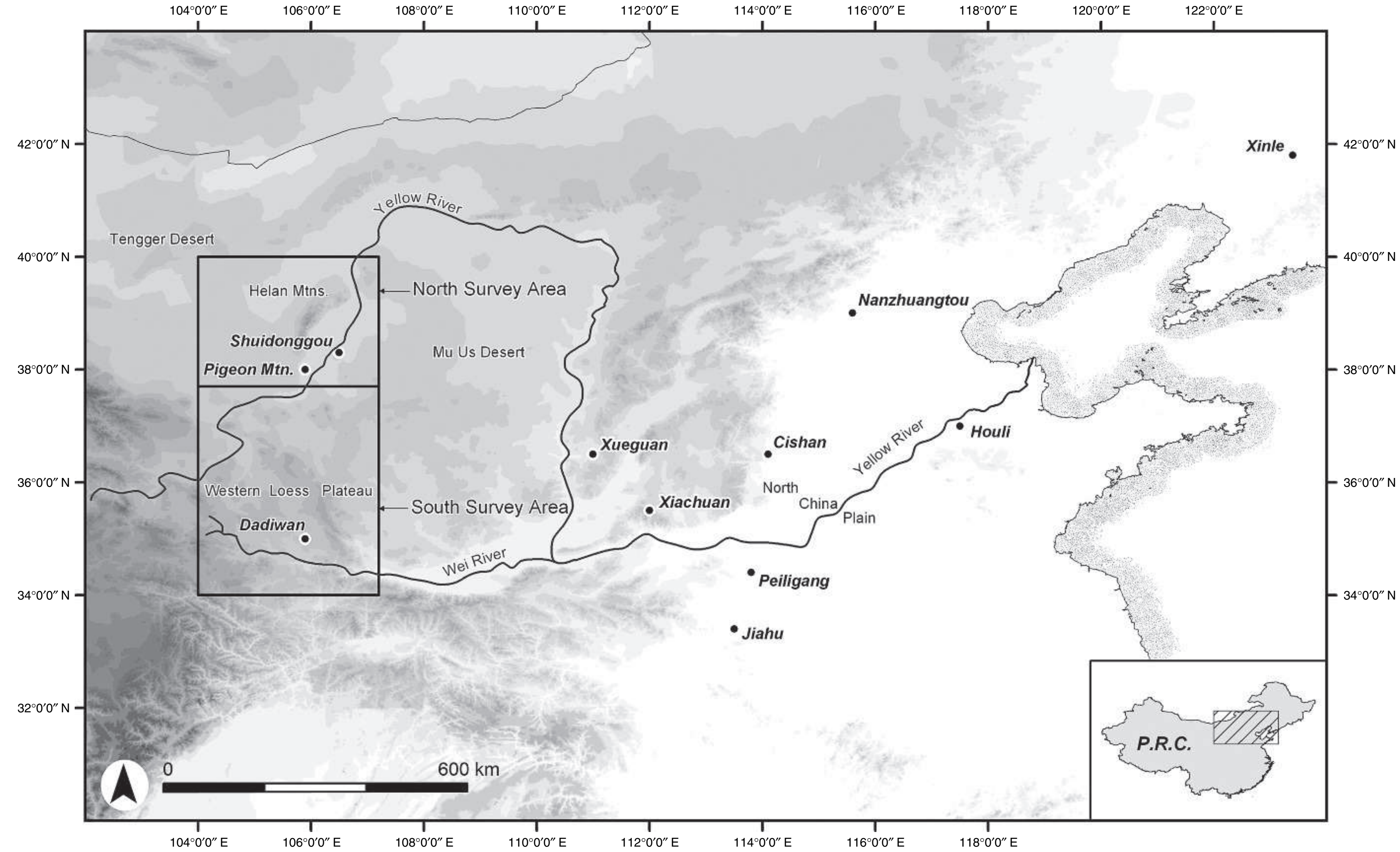

Fig. 4. Map of north China with sites mentioned in text.

shares its roots with the assemblages believed potentially ancestral to Cishan and Peiligang. Upland Dadiwan is much more closely connected to the Late Pleistocene and Early Holocene upland complexes of the upper Yellow River, in the southern Mongolian Plateau, 300–400 km to the north, than to more distant Late Pleistocene and Early Holocene sites like Xueguan (490 km), Xiachuan (560 km) and Nanzhuangtou (970 km). The cultivars, too, were probably different. Dadiwan is the probable location of the domestication of broomcorn millet (*Panicum miliaceum*; Underhill, 1997, p. 121; Yan, 1992, p. 117; Cohen, 1998, p. 22; Shelach, 2000, p. 380), which ripens faster and is more tolerant of cold and drought than foxtail millet (*Setaria italica*; Baltensperger, 1996), which is more suited to the warmer, moister north China Plain.

3.1 Prehistory of the Upper Yellow River – Southwestern Loess Plateau

Our team of Chinese and US scholars has been pursuing this connection since 1989 in a large study area anchored on the Dadiwan-type site (Fig. 4; Bettinger *et al.*, 1990; Bettinger *et al.*, 1994). The northern part of this area is outside the Loess Plateau. Here, expansive sandy deserts (Tengger Desert, Mu Us Desert) run right to the edge of the bottomlands of the upper Yellow River, which flows first east and then north along the eastern front of the north – south trending Helan Mountains. South of the Yellow River, patches of sandy desert increasingly give way to the hilly, rolling topography of the Loess Plateau, rising to the watershed between the Upper Yellow and Upper Wei River drainages, about 50 km north of the Dadiwan site. Data acquired in our research at the major sites of Shuidonggou and Pigeon Mountain, and by others, are sufficient to capture the patterns of change in technology, climate, and adaptation in the northern part of this area beginning about 41,000 years ago that were likely seminal to the development of agriculture in the southern part. Distinct lithic technologies are the signature of three Late Pleistocene – Early Holocene time periods – Shuidonggou, Helan, and Tengger – that frame this discussion.

3.1.1 Shuidonggou Period (41.0–24.0 ka)

The Shuidonggou period is characterized by a distinctive Levallois-like, flat-faced core technology directed toward blade production that is part of the early Upper Paleolithic (EUP) techno-complex of northeast Asia, roughly 40.0–25.0 ka (Brantingham *et al.*, 2001; Brantingham *et al.*, 2004). Dates from the type site (Shuidonggou) in the study area indicate a relatively late fluorescence, from 29.0 to 24.0 ka (Madsen *et al.*, 2001). However, a minimum-limiting date of 41,070 ± 890 ^{14}C yr BP (Beta 161632) on carbonate encrusting a flake from the only other known north China EUP assemblage (also in the study area) suggests that the Shuidonggou period is essentially conterminous with the larger northeast Asian EUP techno-complex. Three cultural deposits exposed in the southern part of our study area (Guyuan 3, 25,228 ± 766 ^{14}C yr BP, CAMS 93161&2; Tong Xin 3, 25, 030 ± 80 ^{14}C yr BP, CAMS 93167&8; Tong Xin 8, 24, 760 ± 220 ^{14}C yr BP, CAMS 93169) are coeval in time with Shuidonggou and belong to the Tong Xin facies of the Chinese EUP (see Barton *et al.*, this volume). The nearest of these is more than 190 km and the farthest more than 260 km, south of Shuidonggou, suggesting the EUP population of north China was more widely distributed, and perhaps larger, than previously thought (see also Gao *et al.*, 2004).

Shuidonggou period settlement patterns are poorly understood, but the blade-oriented technology suggests the use of relatively sophisticated grooved or socketed tools fitted with replaceable end-blade or multiple side-blade insets, hinting at a relatively specialized and residentially mobile adaptation likely oriented to the large herbivores (wooly rhinoceros, *Coelodonta antiquitatis*; horse, *Equus przewalskyi*; ass, *E. hemionus*; antelope, *Spiroceros kiakhtensis*; and gazelle, *Gazella* sp.) represented in the Shuidonggou faunal assemblage (Madsen *et al.*, 2001, pp. 712, 714). Such specialization might account for the failure of the north China EUP to persist into and across the cold, dry LGM, perhaps owing to the diminishing abundance of the large vertebrates that seem to have been important. Goebel (1999) observes a similar contraction of the Siberian EUP during the LGM. Whatever its ultimate fate, there is no post-LGM expression of the EUP anywhere in north China. Indeed north of the Yellow River there is a gap in the archeological record until the beginning of the Helan period at 12.7 ka, which is characterized by a technology quite unlike the EUP. However, hunter-gatherer groups continued to occupy the Loess Plateau, south of the Yellow River, throughout the LGM (see Barton *et al.*, this volume).

3.1.2 Helan Period (12.7–11.6 ka)

In contrast to the blade-oriented EUP, Helan period lithic technology is dominated by a diverse array of spheroids, flake tools, scrapers, gouges and a series of triangular, ovate and bi-pointed bifaces (Helan points) for which the period is named (Madsen *et al.*, 1995; Madsen *et al.*, 1996; Elston *et al.*, 1997; Zhang 1999). We term this technology *macrolithic* – characterized by large tools reduced by coarse percussion, generally using grainy, tough and locally available quartzites and metavolcanics. Millingstones indicate some use of small seeds. Chipped and ground adzes and axes may be present, more surely so in the following Tengger period.

The diversity of tool forms and prominence of those suitable for making and maintaining digging sticks, grinding seeds and pulping fiber, roots and small game, imply the use of a broader range of species, and smaller ones, and a greater use of plants than in the Shuidonggou period. This, and the substantial size of Helan assemblages, suggests an adaptation less residentially mobile than during the

Shuidonggou period. Sites are characteristically located on the margins of expansive dune fields in proximity to uplands, striking a locational compromise between these distinctly different resource opportunities. This provided immediate access to the waterfowl, small game, plants and herding ungulates associated with interdunal ponds and wetlands, and logistical access to more solitary ungulates and a different range of plants in the sand-free piedmonts and uplands. Dune ponds and wetlands are most productive during the summer-fall wet season and progressively less attractive with desiccation during the winter-spring dry season, when residence probably shifted to piedmonts and uplands where springs provided water. In comparison to those on dune margins, Helan upland sites are fewer and their assemblages generally larger and more diverse, suggesting the use of especially favored locations as relatively permanent base camps during this lean dry season. The more numerous dune margin sites, on the other hand, argue that dune plants and animals were much preferred, attracting the bulk of Helan settlement during the season when resources were most abundant (wet season) during a time period of relative resource abundance. Milling equipment suggests that seeds were at least a minor dune-field attraction during this period of climatic amelioration, which ended with an abrupt and rapid return to the cold-dry glacial environments that characterized the Younger Dryas (Madsen *et al.*, 1998). Lake levels dropped, and interdunal lakes, ponds and wetlands frequently dried up and filled with wind-blown sand. Our Tengger period broadly coincides with the Younger Dryas.

3.1.3 Tengger Period (11.6–10.1 ka)

Technology changed with climate in the Tengger period: macrolithic technology diminished in relation to *microlithic* technology: soft-hammer percussion and pressure-flaked thumbnail end-scrapers, bifaces, arrowheads, flake tools, microblades, retouched microblades and pebble microcores. There was a parallel shift in raw material use, from quartzites and metavolcanics, to cryptocrystalline cherts and chalcedonies. Most of these microlithic elements are present in the preceding Helan period. But while the range of chipped stone tool types is about the same overall, Tengger assemblages are more evenly balanced owing to the greater investment in an array of sophisticated technologies (e.g., microblades) that suggest resource specialization, much as in the blade-dominated Shuidonggou period, but targeting more and smaller species.

Sampling error and preservation probably explain why the Tengger assemblage lacks milling tools and is richer in faunal remains than the Helan assemblage. Nevertheless, these differences are consistent with our view that subsistence narrowed significantly during the Younger Dryas – with hunting increasing in importance relative to gathering – and that this is behind the increase in microblades. Dune-field resources, including waterfowl, small game and ungulates, clearly became more important. Microblades, microcores and other microlithic technology indicate continued use of dune margin camps in the wet season and upland base camps in the dry season, when resources were scarce. The many more sites scattered throughout dune-field interiors feature microlithic technology exclusively, however, attesting to a more intensive pattern of wet season dune use that began in the Tengger period and extended well into the Holocene. The sheer abundance of these dune interior sites makes it fairly clear that dune resources were preferred during seasons of relative abundance, as in the Helan period.

3.1.4 Early Holocene (10.1 ka)

The Helan period extends through the first summer monsoon episode of the Holocene (10.1 ka), a warm-wet interval of interdunal lake and marsh refilling that abruptly terminated the Younger Dryas (Madsen *et al.*, 2003). Helan groups seem to have responded by further intensifying dune procurement using a technology increasingly given to microblades in an increasingly dune-centered settlement pattern. The growing opportunities for plant procurement were likely also turned to advantage. The wild form of broomcorn millet (*Panicum miliaceum*) was probably used as a seasonal food and perhaps stored to prolong occupation of interdunal camps with access to more highly valued resources. It is difficult to be certain about much of this, however, because our Early Holocene archeological record ends here. No archeological site anywhere in our northern study area has produced a radiocarbon date that falls between 10.1 and 7.9 ka. In the southern study area the record picks up still later, at the early agricultural site of Dadiwan, at 7.0 ka (6, 950 ± 90, ^{14}C yr BP, BK80025; Institute of Archaeology 1991), 340 km south of the dune and upland Helan sites of the upper Yellow River.

3.2 The Gap in the Record

The absence of Early Holocene dates in the northern part of our study area is probably a function of our project design; we did not date likely Early Holocene sites. The same cannot be said for the southern part of the study area. The dearth of known Early Holocene sites here does not reflect either sampling error or lack of effort. The Gansu Institute of Archaeology has records for 3007 sites that together present 3601 cultural components in the broader Dadiwan region (102.4°–108.7° E, 33.5°–37.2° N; Table 1). Of these, none is Early Neolithic. This, and the dearth of earlier Paleolithic and Late Paleolithic sites (just 19 in total, all single component), makes it most improbable that the agricultural Dadiwan complex (i.e., Middle Neolithic) emerged from a local hunter-gatherer base. That Dadiwan sites, on the other side of this temporal gap, are so rare (three in total), and at the same time all multicomponent (with Yangshao and later elements), attests instead to a trajectory of continuous agricultural development whose local roots are no deeper than Dadiwan itself. The absence of human occupation in the Dadiwan region during

Table 1. Temporal distribution of components in Gansu Institute Survey.

Paleolithic/Late Paleolithic	Early Neolithic	Middle Neolithic (Dadiwan)	Early Yangshao	Middle/Late Yangshao	Qijia
		(Cal yr BP)			
> 10,000	10,000–8000	8000–7000	7000–6000	6000–5000	5000–4000
19	0	3	62	1542	1975

the Early Holocene is hard to explain, but wetland-swamp deposits indicating the onset of conditions that would have been highly attractive to hunter-gatherers are a recurrent signature in stratigraphic sections 7.0–5.5 ka throughout the western Chinese Loess Plateau, denoting a warm-wet climax within what Feng *et al.* (2004) term the Mid-Holocene Megahumid event. This mountainous region would have been much less attractive in the absence of these extensive wetlands.

The Dadiwan regional chronology thus repeats the familiar north China pattern, noted long ago (e.g., An, 1988, Fig. 1) and commented upon by Lu (1999): the interval 10.0–8.0 ka is remarkably under-represented and the "Early Neolithic" of north China's culture history essentially non-existent. Radiocarbon data are somewhat deceiving in this sense: of the 118 reliable dates we have been able to assemble for all of north China that fall between 14.0 and 6.0 ka, no fewer than 11 (9.3%) are between 10.0 and 8.0 ka. While this is still less than the frequency of dates falling in this interval in Near East (264, 53%) and Japan (21, 25%) assembled for rough comparison, a temporal gap is not clearly apparent (Table 2, 3). However, 10 of these 11 north China dates are from just one site, Nanzhuangtou (Guo and Li, 2002). And, as our sites on the Upper Yellow River stand in relation to Dadi-

Table 2. Distribution of representative radiocarbon dates for the period 14 – 6 ka from north china, the Near East and Japan (see Table 3 for sources).

	14–13 ka	13–12 ka	12–11 ka	11–10 ka	10–9 ka	9–8 ka	8–7 ka	7–6 ka	Total
North China.	0.05	0.05	0.05	0.12	0.07	0.03	0.28	0.36	118
Near East.	0.04	0.05	0.06	0.18	0.19	0.34	0.11	0.02	494
Japan	0.04	0.04	0.01	0.06	0.08	0.17	0.25	0.35	83

Table 3. Sources for Radiocarbon Data Referenced in Table 2 and Fig. 5.

No. of dates	Reference	Region/culture/site
24	IA-CASS, 1991	China
1	IA-CASS, 1997	China
1	IA-CASS, 2001	China
2	Anderson, 2004	Xinle
1	Bettinger *et al.*, 2005a	Peng Yang 4
1	Bettinger *et al.*, 2005b	Dadiwan
5	Elston *et al.*, 1997	Pigeon Mountain
1	Fu, 2003	Qingtoushan
19	Li *et al.*, 2003:34	Jiahu
1	Lu, 1998	Daxingtun
8	Lu, 1999: Table 4(1)	North China preagricultural
36	Lu, 1999: Table 4(7)	North China Neolithic
1	Madsen *et al.*, 1998	Pigeon Mountain
1	Madsen *et al.*, 2003	Jilantai
1	RDL-BD, 1994	Nanzhuangtou
10	Shelach, 2000:371	Xinglongwa, NE China
5	Yuan *et al.*, 1998	Shizitan
129	Byrd, 1994	Near East
365	Kuijt and Bar-Yosef, 1994	Near East
4	Serizawa, 1974	Japan
79	Keally and Muto, 1982	Japan

wan, 340 km to the south, so does Nanzhaungtou in relation to the early centers of millet agriculture on the north China Plain to the south, Houli (277 km), Cishan (305 km) and Peiligang (536 km): Nanzhaungtou articulates with these sites in time but not space. The situation in north China is better appreciated when our sample of radiocarbon dates ($n = 118$) are plotted in degrees latitude north (Fig. 5). Here the temporo-spatial separation between the sites representing the early centers of north China agriculture (Houli, Cishan, Peiligang, Xinle, and Dadiwan) and their potential ancestors, is clearly apparent. In none of these cases is there a credible evidence for the development of agriculture from a local base.

4. Middle Holocene Population Movement from the Upper Yellow River

Although we suspect the process leading to agriculture at Cishan and Peiligang may have been similar, our major concern is with the Dadiwan complex. Given the dearth of Late Pleistocene–Early Holocene sites representing an intensive hunter-gatherer adaptation from which it might be locally derived, the most likely explanation for appearance of broomcorn millet agriculture at Dadiwan is that it was developed by intensive hunter-gatherers moving south, out of the deserts along the Upper Yellow River, in the northern part of our study area. While the evidence suggests a generally benign climate in these deserts during the Early Holocene (Shi *et al.*, 2002), with summer monsoon episodes at 9.3 and 8.0 ka (in addition to the one at 10.1 ka previously mentioned; Madsen *et al.*, 2003), these were interleaved with droughts (see Wünnemann *et al.*, this volume) and it is clear that the overall trend was toward longer dry spells and shorter wet ones, leading to a deep Mid-Holocene drought from 6.0 to 4.4 ka (Chen *et al.*, 2003). In the most plausible scenario, former upper Yellow River desert dwellers, already familiar with wild broomcorn millet, probably drifted progressively southward with each drought, increasingly attracted by the highly productive wetland/swamp environments that became established in the river bottoms of the western Chinese Loess Plateau during the climax of the Mid-Holocene Megahumid (Feng *et al.*, 2004). It is significant in this regard that the Megahumid component of the stratigraphic section at Dadiwan (7.5–5.0 ka; Fig. 6 in Feng *et al.*, 2004) is characterized not by wetland/swamp deposits but rather by alternating couplets of wetland/swamp and fluvial deposits attesting to frequent, but short-term, flooding that would have produced disturbed mud flat microhabitats highly suited to agriculture, which likely explains why agriculture first appeared at Dadiwan specifically, at 7.0 ka. Since Dadiwan is agricultural from the start, however, these groups must have become low-level food producers before they arrived at Dadiwan, but after they left the upper Yellow River, where evidence of early agriculture is evidently lacking. It is quite thinkable that as these groups drifted further south into the unfamiliar Chinese Loess Plateau, they may have intensified their use

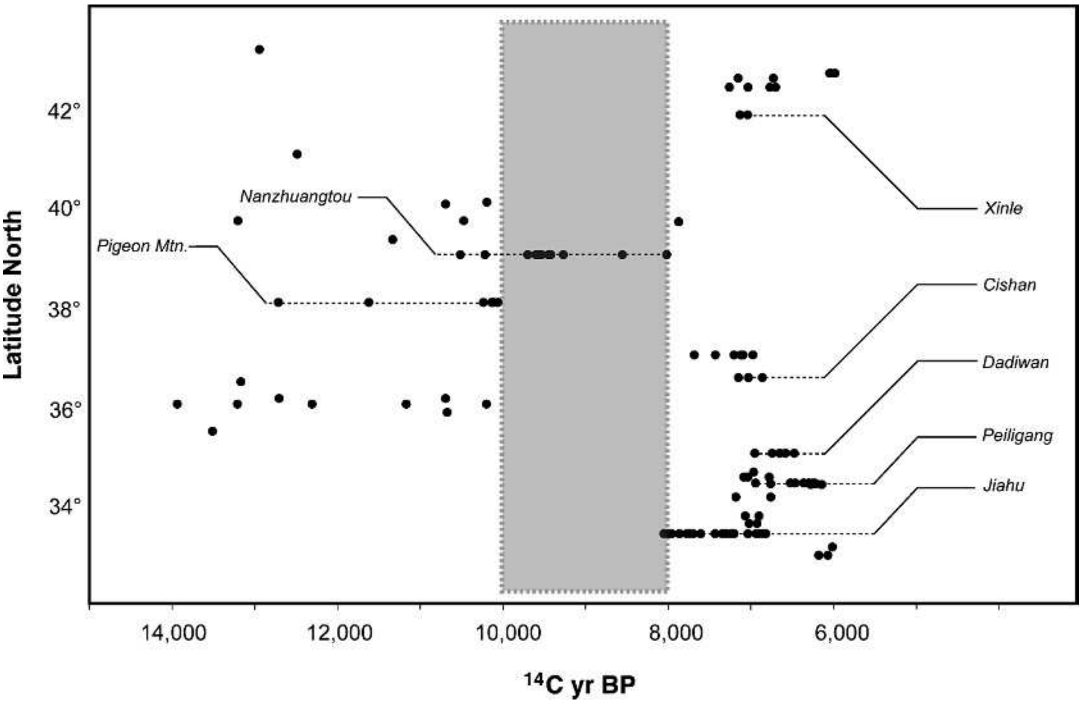

Fig. 5. Radiocarbon dates ($n = 118$) from north China between 14,000 and 6000 ^{14}C yr BP plotted by latitude. Callouts on the right identify early agricultural sites, those on the left identify preagricultural sites. The shaded area depicts the archeological hiatus over much of north China between 10,000 and 8,000 ^{14}C yr BP (see Table 3 for sources).

of the fast ripening (60–90 days; Baltensperger, 1996) broomcorn millet in a small way, casually sowing it around fall-winter settlements, mainly as a "catch crop," when wild resources were observed to be unpromising. The output of this low-level form of food production would have qualitatively increased simply as a consequence of its introduction to the muddy flood plains around Dadiwan, in short order transforming a minor fallback food into a reliable crop.

Despite this improved productivity, it is probably best to regard the initial phase of Dadiwan (Dadiwan I) as representing a form of what Smith (2001) terms low-level food production: Dadiwan I components are not only rare, they are characteristically thin, suggesting small and fairly mobile populations. In contrast to low-level food production elsewhere, however, this pattern is comparatively short lived. Without having to contend with a long established population of hunter-gatherers resistant to the establishment of territories, the holding of private agricultural plots and the hoarding of food, the Dadiwan system rapidly intensified and expanded. In scarcely one thousand years, it produced Early Yanshao settlements like Banpo and Jiangzhai, which were clearly not inhabited by low-level food producers. The initial component at Jiangzhai (Jackes and Gao,1994), for example, represents an organized, intensive agricultural village, with five groupings of houses (120 in all) laid out around a $4000\,\mathrm{m}^2$ central plaza, a full complement of hearths ($n > 200$), storage pits ($n > 300$), animal pens, a separate kiln area and a cemetery with three distinct sections (each with about 26 urns and 50 primary burials, displaying a high frequency of violence; Jackes and Gao, 1994).

5. Conclusion

The emergence of millet agriculture in northwest China differs in two ways from the trajectory of early agriculture observed elsewhere around the world, notably Mesoamerica and the Near East. First, millet agriculture did not emerge from a local hunter-gatherer base, but was rather introduced by groups migrating into areas that were either uninhabited or only sparsely occupied. Second, early millet agriculture expanded and intensified quite rapidly, with only a short interval of low-level production. In places like the Near East, on the other hand, agriculture emerges from intensive patterns of hunting and gathering that cap long histories of in situ development and is characterized by an initial stage of low-level food production lasting four or five thousand years. It is unlikely these differences are coincidental. What these data suggest is that when early agriculture develops in situ, and has to compete with an existing hunter-gatherer base, it expands slowly, as in the Near East; when it develops or appears in places where it does not have to compete with an existing hunter-gatherer base, it expands rapidly, as in the Dadiwan to Banpo transition. This, in turn, suggests that it is hunter-gatherer social conventions precluding the ownership of land and hoarding of resources that hinder the intensification of low-level food production. Where these are absent, agriculture expands rapidly. Where they are present, agriculture can intensify only by the slow process of group selection, in which groups that preclude landholding (hence intensive agriculture) are replaced, one by one, by agricultural groups that permit it. It is the slow pace of group selection that explains the long intervals of low-level food production.

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Part IV

REGIONAL AND CHRONOLOGICAL PERSPECTIVES

8

Late Pleistocene climate change and Paleolithic cultural evolution in northern China: Implications from the Last Glacial Maximum

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Abstract

Temporal and spatial patterns in archeological data from Pleistocene north China suggest strong correlations between climate change and culture change, but only in extreme cases. In these cases, climate has an immediate impact on human mobility, which is severely constrained during the pronounced cold/dry intervals of the Pleistocene. As high mobility becomes incompatible with the environmental limitations of extreme intervals, such as the Last Glacial Maximum, previously disparate mobile human groups aggregate and compete for limited and spatially segregated resources. During such times, regional cultural variation evolves in isolation and natural selection acts on group-level adaptations, facilitating the evolution of cohesive and cooperative social networks. The process of group selection further allows for the rapid diffusion of cultural and technological innovation and may explain the rapid diffusion of microblade technology throughout northeast Asia during the post-glacial period. While climate change does present challenges to human survival and may promote alternative adaptive strategies, rapid cultural evolution is driven primarily by group formation, between-group competition, and the mechanics of cultural transmission. The degree to which climate change mediates these interactions is the extent to which climate should be implicated in cultural evolution.

1. Introduction

The influence of climate change on human cultural evolution is regularly assumed but rarely demonstrated. In truth, we have a relatively poor understanding of how individuals, much less groups, respond to long-term environmental change. What we do understand, we understand on relatively short time scales and our limited experience provides us with little ability to suggest how individuals, traditions, or institutions will react or respond to sustained or punctuated environmental change. This situation is due, in part, to the difficulty of collecting and identifying the appropriate data sets with which to track the correlation between environment and culture and to the difficulty of controlling the many interactions that separate a suspected cultural effect from a proposed environmental cause. Perhaps more importantly, our perspective is limited by an historical adherence to the recent Holocene, a period of relatively subtle environmental change marked by rapid, cumulative cultural evolution maintained and accelerated by large numbers of continuously interacting individuals. That is not to say that climate has no bearing on Holocene human history, merely that recognizing the impact of climate change on cultural evolution is exceedingly difficult. For this reason, we turn our attention to the Pleistocene.

Paleolithic hunter-gatherers had a range of potential strategies with which to adapt to the dramatic environmental variability of the late Pleistocene. Independent invention of unique tool types or modification of existing tool types are technological solutions to local problems. Changes in mobility, food storage, or diet-breadth are organizational adaptations. And risk-buffering strategies such as long distance resource exchange, codified rules for mate selection and exchange, territorial defense and land ownership, and internal divisions of labor and class are institutional adaptations that require coordinated behavior from a range of individuals to evolve. In all likelihood, some combination of technological, organizational, and institutional adaptation enabled Paleolithic foragers to cope with the often-punctuated and, by comparison to the Holocene, extreme, environmental change characteristic of the Pleistocene.

Equating cultural evolution with climate change is complex. Clearly, changes in the local environment evince local reactions, most of which are regular features of a very flexible repertoire of human behavior. In a constantly variable world, flexibility itself is an adaptation that evolves to meet the challenges of a relatively brief window of evolutionary relevance, perhaps on the order of only a few human generations. Overly rigid or specialized adaptations do not emerge in variable environments. The issue is clearly a matter of scale – a question of how much and how fast environments change (see Madsen and Elston, this volume), and whether or not the mechanics of human cultural evolution generate behavioral adaptations capable of tracking this change. Any adaptation that initially evolves *because* of its ability to cope with the resource stresses associated with environmental variation is naturally trained to accommodate most subsequent variations in climate and environment. Essentially, most environmental change will have little impact on the range of human behaviors specifically adapted to environmental

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variability itself. Therefore, we must look to periods marked by significant departures from the environmental context of Pleistocene cultural evolution to see if and how human culture responds to environmental change.

Here, we focus on the degree to which environmental change affects the settlement–subsistence strategies of Paleolithic foragers. Our analysis begins with a brief discussion of human mobility as an adaptive strategy. We then present a simple method for evaluating change in human mobility using radiocarbon data drawn from Pleistocene archeological sites across northern China. The patterns in these data enable an assessment of the correlation between environmental change and human biogeography. Recent archeological research focused on human occupation of the western Loess Plateau during the Last Glacial Maximum (LGM) helps to illustrate the behavioral and demographic context of human cultural evolution during periods of extreme environmental change. We conclude by suggesting that the LGM played a critical role in shaping human demographic processes and advance an hypothesis to account for the rapid and widespread changes in human cultural evolution during the postglacial period. The prolonged environmental deterioration characteristic of the LGM was unprecedented in the environmental history of northeast Asia, and it stands to reason that such conditions may have engendered novel behavioral solutions from the human populations that survived it.

2. Hunter-gatherer Mobility

The migratory patterns of *Homo sapiens* are the subject of considerable study and debate. Much of our understanding of hunter-gatherer mobility comes from ethnographic observation and historical reconstruction of extant hunter-gatherers during the twentieth century (e.g., Steward, 1938). Inasmuch as subsistence–settlement patterns, and therefore mobility, can be considered adaptations, it may also be true that multiple adaptations will emerge as solutions to similar environmental conditions (Steward, 1937; Steward, 1938; Bettinger and Baumhoff, 1982; Bettinger and Baumhoff, 1983). In this sense, climate is not a direct determinant of cultural change. However, human groups do organize their settlement–subsistence strategies around environmental limitations, and research suggests that changes in the organization of mobility strongly affect sociopolitical organization, trade, territoriality, demography, intergroup dynamics, identity, and enculturative processes (Kelly, 1992). From a theoretical standpoint then, variation in human mobility provides the foundation for human evolutionary change, and our understanding of Paleolithic cultural evolution is dependent upon understanding hunter-gatherer mobility.

For many animals, relocation is a regular and recurrent response to local resource depression. The adaptive logic of this solution is based on the economic predictions of models drawn from optimal foraging theory (Winterhalder and Smith, 1981; Bettinger, 1991; Smith and Winterhalder, 1992) and includes deterministic and stochastic solutions, both of which are built upon the principle of marginal utility (Charnov *et al.*, 1976; Charnov, 1976). The deterministic "patch choice" model generates predictions for relocation given the declining value of a current resource patch, the expected value of an alternative patch, and the cost of travel between patches. A generalized prediction of the patch choice model suggests that costs associated with relocation in a relatively unpopulated landscape are low when compared to the costs associated with extracting enough energy to survive from a dwindling resource base. The stochastic model opens the deterministic model to the issue of "risk" (Stephens, 1981; Stephens and Charnov, 1982). In optimal foraging parlance, risk is narrowly defined as the variance around the expected mean value of the foraging budget; the greater the variance, the greater the risk associated with acquiring the expected value of the total foraging effort. In a perfect world (i.e., the deterministic model), the expected value is always achieved and there is no risk. In a more realistically variable or unpredictable environment, the variance around the mean expected payoff may be so great that the probability of acquiring the minimum amount of resources required for survival is dangerously low.

Historical and ethnographic examples of resource acquisition demonstrate that optimal solutions to variable environments may be reached through acquiring resources from multiple sources. By combining the expected returns (with known means and standard deviations) of multiple sources, an individual or a small integrated group reduces the net hazards of subsistence shortfall (McCloskey, 1975; Winterhalder, 1990; Goland, 1991). In the absence of other strategies for averaging risk, human foragers move frequently to increase the number of places they acquire resources. In so doing, foragers average the risk of subsistence shortfall spatially and temporally by incorporating more foraging patches over a given period of time. This "residential mobility" is therefore a simple, effective strategy for human foragers to manage the risks and hazards of resource depression and does not require the additional costs or selective pressures associated with complex tool technology, diet breadth expansion, or the evolution of group-functional behavior.

Essentially, mobility enables human foragers in an open, relatively unpopulated landscape to escape local resource depression simply by moving camp. Mobility and relocation may therefore be considered "first-order" responses to environmental variability. Alternative solutions to risk management, such as storage, diet-breadth expansion, sharing, and other group-functional means of averaging the risks of resource shortfall may evolve under a variety of conditions, but only when mobility is constrained by the limitations of the social or ecological environment.

3. Late Pleistocene Human Biogeography in Northern China

3.1 Recent Ideas about Environmentally Mediated Culture Change

Researchers working primarily in Siberia and the Russian Far East propose that the Early Upper Paleolithic (EUP) – the cultural and behavioral techno-complex that accompanied and perhaps enabled widespread occupation of northeast Asia during marine isotope stage 3 (MIS3) – met an abrupt end with the onset of the LGM (Goebel, 1999; Goebel, 2002; Goebel, 2004). They argue that extreme environmental deterioration during the LGM reduced regional human populations to unsustainable levels and suggest that the cultural traditions that define the EUP disappeared with their makers (e.g., Brantingham *et al.*, 2004b). Furthermore, they suggest that with post-glacial environmental amelioration, a completely different adaptive strategy characterized by the use of microblades, composite inset weaponry, and high foraging mobility, emerged and expanded rapidly into regions left vacant by the regional population bottlenecks of the LGM. For these researchers, a gap in the radiocarbon record of Siberia between 22.8 and 21.5 ka[1] confirms the role of environmental change in the culture-history of northeast Asia, implying that punctuated bursts of cultural evolution result from either regional extirpation or (re)colonization of virgin landscapes (Goebel, 1999; Goebel, 2002; Goebel, 2004; Brantingham *et al.*, 2004b). A similar story is extended to explain the end of the EUP and the onset of the Late Upper Paleolithic (LUP) in northern China (Brantingham, 1999) and on the Qinghai–Tibet Plateau (Brantingham *et al.*, 2003) (but see Brantingham *et al.*, this volume, and Madsen *et al.*, 2006). If true, these examples provide strong support for the deterministic role of environmental change in cultural evolution.

In 2002, archeological survey in the western Loess Plateau recorded and sampled two sites (ZL05 and PY03) with radiometric age estimates within the boundaries of the LGM (Ji *et al.*, 2005; Bettinger *et al.*, n.d.). However, the stone tool assemblages from these and other sites in the western Loess Plateau are distinct from the prepared, flat-faced core-and-blade technology evident at Shuidonggou, Locality 1 – the type-site for the EUP expression in northern China. The LGM sites discovered in 2002 provide temporal anchors for the modified settlement–subsistence pattern that succeeds the EUP in the western Loess Plateau and further suggest that the region was not abandoned during the LGM. While it seems clear that the classic *markers* of the EUP disappeared from north China during the LGM, it seems equally clear that *people* did not. What role, if any, did the comparatively extreme environmental change during the LGM play in the culture history of the northeast Asian Upper Paleolithic?

3.2 Regional Climate Change and Human Biogeography

Paleolithic deposits throughout the old world are typically defined on the basis of lithic assemblages comprised of recurrent tool forms and, more frequently, the remains of tool manufacturing debris. In China, hundreds of Paleolithic sites have been identified on the basis of stone tool typology (Gao and Norton, 2002; Cohen, 2003). However, because tool use and evolution are subject to local variation, migration, and differential rates of innovation, tool typology is an ineffective time marker at the resolution necessary to evaluate correlation between climate change and cultural evolution. For this reason, our analysis of human settlement dynamics in northern China during the Late Pleistocene includes only those Paleolithic sites with radiocarbon age estimates from culture-bearing deposits. Other methods for dating archeological deposits are excluded from this analysis for the sake of consistency and because they are either methodologically equivocal or insufficiently standardized. Table 1 provides the known range of radiocarbon estimates from cultural deposits in north China between 45 and 10 ka.

Radiocarbon data sets are widely employed to identify both synchronic and diachronic trends in human activity, including spatial distributions of contemporaneous cultural patterns as well as prehistoric population dynamics (see Rick, 1987). In northern China (north of 34° latitude), the spatial distribution of radiocarbon data demonstrates that regions below 41° latitude were continuously occupied from the MIS3, through the LGM, and into the post-glacial Late Pleistocene (Figures 1 and 2A–C). However, north of 41° latitude, northeast China appears uninhabited during the LGM, 24–18 ka[2] (Figure 2B). This pattern is attributed to a southward migration of human groups in response to the expansion of northern deserts and the concomitant retreat of temperate grasslands (Ji *et al.*, 2005). While this may account for the depopulation of northeast China, the radiocarbon data suggest that the arid landscape occupied by the EUP hunter-gatherers at Shuidonggou was not completely abandoned during the LGM. Furthermore, despite the southward expansion of desert vegetation (Zheng *et al.*, 1998; Xie *et al.*, 2002) synchronous with the southward expansion of the Gobi (Feng *et al.*, 1998) and Mu Us deserts (Zhou *et al.*, 2002), the Loess Plateau was also occupied during the LGM. Desertification, in itself, is insufficient to explain the dramatic cultural evolution apparent during the late Pleistocene.

Beyond the general pattern of southward human migration, we ask how the environmental changes characteristic of the LGM might have forced human groups to modify their foraging behavior and therefore their settlement patterns. To do this, we look to the cumulative probability distribution of calibrated radiocarbon dates from north China for correlations with regional environmental change.

A 2D dispersion calibration (Weninger, 1986), such as that generated by CalPal calibration software (Weninger *et al.*, 2005), incorporates radiocarbon age estimates and their

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[1] Ages reported as 'ka' are calendar years before present.

[2] Regional variations in global environmental patterns confound absolute definition of the LGM, broadly classified as a period of maximum global ice volume. For the sake of clarity and comparison, we follow Bard (1999) in defining the LGM not by ice volume, but as an interval bracketed by two marked temperature minima, classified as Heinrich Events (HE), identified in both Greenland ice-core records and North Atlantic sediment cores. Based on radiometric dating of the sea core evidence for the end of the HE2 and the abrupt onset of HE1, the LGM dates to between 20,400 and 15,000 ^{14}C yr BP (24,500–18,300 Cal yr BP) (Elliot *et al.*, 1998).

Table 1. Radiocarbon data from Paleolithic north China. Uncalibrated dates (^{14}C yr BP) are based on the Libby half-life of 5568. The 2-σcalibrated midpoints (Cal yr BP) and range (+/−) are generated using CalPal software v. CalPal_ 2005_SFCP (Weninger et al., 2005).

site	lab.#	lon.DD	lat.DD	material	^{14}C yr BP	+/−	Cal yr BP	+/−	reference
Nanzhuangtou	BK87083	115.600	39.000	Silt	9,266	100	10,450	260	RDL-BD, 1994
Nanzhuangtou	BK86121	115.600	39.000	charcoal	9,416	95	10,720	360	RDL-BD, 1994
Nanzhuangtou	BK87084	115.600	39.000	Silt	9,446	120	10,780	440	RDL-BD, 1994
Daxingtun	PV0368	123.883	47.033	Bone	9,460	80	10,800	380	Lu, 1998
Nanzhuangtou	BK97093	115.600	39.000	charcoal	9,533	100	10,880	360	RDL-BD, 1994
Nanzhuangtou	BK86120	115.600	39.000	charcoal	9,596	160	10,920	440	RDL-BD, 1994
Nanzhuangtou	BK89064	115.600	39.000	charcoal	9,572	90	10,930	320	RDL-BD, 1994
Nanzhuangtou	BK87086	115.600	39.000	Silt	9,698	100	11,020	340	RDL-BD, 1994
Pigeon Mtn (QG3)	Beta 086732	105.852	38.044	charcoal	10,060	60	11,600	320	Elston *et al.*, 1997
Pigeon Mtn (QG3)	Beta 094119	105.852	38.044	charcoal	10,120	60	11,740	360	Madsen *et al.*, 1998
Shizitan	BA93186	110.067	36.000	burned bone	10,194	540	11,790	1,480	Yuan *et al.*, 1998
Zhangjiabo	BK85031	124.700	40.050	charcoal	10,190	120	11,860	520	IA-CASS, 1991
Nanzhuangtou	BK87075	115.600	39.000	charcoal	10,213	110	11,920	500	Lu, 1999: Table 4(7)
Pigeon Mtn (QG3)	Beta 097241	105.852	38.044	charcoal	10,230	50	11,950	220	Elston *et al.*, 1997
Huangjiaweizi	ZK2078	124.050	46.017	shell	10,290	140	12,100	620	IA-CASS, 1991
Zhoukoudian (Upper Cave)	ZK136-0(1)	115.917	39.683	bone	10,466	360	12,150	1,020	Lu, 1999: Table 4(1)
Xiaonanhai	ZK665-0(665)	114.117	36.117	bone & charcoal	10,689	500	12,360	1,320	Lu, 1999: Table 4(1)
Nanzhuangtou	BK87088	115.600	39.000	wood	10,509	140	12,400	440	Lu, 1999: Table 4(7)
Hutouliang	PV0156	114.150	40.017	bone	10,689	210	12,530	560	Lu, 1999: Table 4(1)
PY04	CAMS 94202	106.646	35.835	charcoal	10,670	40	12,690	80	*reported here*
Qingtoushan	ZK1374	124.308	45.287	fossil bone	10,940	170	12,900	280	Fu, 2003
Shizitan	BA93190	110.067	36.000	bone	11,166	110	13,070	260	Yuan *et al.*, 1998
Zalainuoer	PV0171	117.583	49.350	charcoal	11,330	130	13,230	260	IA-CASS, 1991
Nanmo	ZK2888	112.400	39.300	charcoal	11,331	166	13,240	340	IA-CASS, 1997
Zalainuoer	PV0015	117.583	49.350	charcoal	11,440	230	13,340	440	IA-CASS, 1991
Daxingtun	PV0369	123.883	47.033	bone	11,470	150	13,370	300	Lu, 1998
Pigeon Mtn (QG3)	Beta 086731	105.852	38.044	charcoal	11,620	70	13,500	160	Elston *et al.*, 1997
Shizitan	BA93187	110.067	36.000	burned bone	12,303	190	14,440	720	Yuan *et al.*, 1998
Anzhangzi	ZK3076	119.717	41.017	bone	12,482	157	14,710	600	IA-CASS, 2001
Pigeon Mtn (QG3)	Beta 097242	105.852	38.044	charcoal	12,710	70	15,140	240	Elston *et al.*, 1997
Xiaonanhai	ZK170-0	114.117	36.117	bone	12,705	220	15,320	1,160	Lu, 1999: Table 4(1)
Mingyuegou	WB78-44	128.917	43.117	tooth	12,940	550	15,680	1,980	IA-CASS, 1991
Xiaonanshan	PV0719	134.033	46.783	fossil bone	12,910	410	15,720	1,720	IA-CASS, 1991
Xueguan	BK81016	111.000	36.450	charcoal	13,167	150	16,220	960	Lu, 1999: Table 4(1)
Shizitan	BA93188	110.067	36.000	burned bone	13,207	220	16,250	1,120	Yuan *et al.*, 1998
Zhoukoudian (Upper Cave)	OXA391	115.917	39.683	bone	13,200	160	16,270	1,000	Lu, 1999: Table 4(1)

Xiachuan (Shunwangping)	ZK762	112.033	35.450	charcoal	13,507	300	16,500	1,220	Chen and Wang, 1989
Shizitan	BA93189	110.067	36.000	burned bone	13,935	250	17,330	360	Yuan *et al.*, 1998
Xiawangjia	?	103.379	35.645	?	14,081	150	17,400	200	Xie, 1991
Shizitan	BA93191	110.067	36.000	bone	14,305	160	17,620	360	Yuan *et al.*, 1998
Xiachuan (Locality 1)	ZK385	112.033	35.450	charcoal	15,936	900	19,280	1,900	Chen and Wang, 1989
TX04	CAMS 94204	105.790	36.778	charcoal	16,460	45	19,670	260	Ji *et al.*, 2005
Xujiayao	ZK0670	113.733	40.367	fossil bone	16,440	2,000	19,830	4,620	IA-CASS, 1991
Shuidonggou (Locality 1)	PV0331	106.333	38.100	bone	16,762	210	19,980	580	IA-CASS, 1991
ZL05	Beta 197631	106.097	35.281	charcoal	16,750	70	20,070	360	*reported here*
Mengjiaquan	?	117.783	39.867	?	17,005	205	20,190	480	Lu, 1999: 35
Gulongshan	PV0225	122.167	39.517	fossil bone	17,090	240	20,390	780	IA-CASS, 1991
Yuhonghe	PV862	109.817	34.917	bone	17,730	500	21,230	1,280	Gao, 1990
Xiachuan (Shanshanyan)	ZK494	112.033	35.450	soil	17,855	480	21,350	1,300	Chen and Wang, 1989
Xiachuan (Shanshanyan)	ZK497	112.033	35.450	peat	18,035	480	21,520	1,320	Lu, 1999: Table 4(1)
Qiangyangdong	BK82067	124.100	39.800	charcoal	18,090	320	21,620	1,100	IA-CASS, 1991
Zhoukoudian (Upper Cave)	ZK136-0(2)	115.917	39.683	bone	18,340	420	21,890	1,020	Lu, 1999: Table 4(1)
PY03	CAMS 94203	106.645	35.835	charcoal	18,350	70	22,080	400	Ji *et al.*, 2005
ZL05	CAMS 95088	106.097	35.281	charcoal	18,920	520	22,700	1,300	Ji *et al.*, 2005
Xiachuan (Shunwangping)	ZK634	112.033	35.450	charcoal	19,046	600	22,820	1,400	Chen and Wang, 1989
Xiachuan (Locality 2)	ZK393	112.033	35.450	charcoal	20,115	600	24,030	1,540	Chen and Wang, 1989
ZL05	Beta 197633	106.097	35.281	charcoal	20,220	90	24,140	240	*reported here*
ZL05	Beta 197632	106.097	35.281	charcoal	21,180	100	25,370	520	*reported here*
Xiachuan (Locality 1)	ZK384	112.033	35.450	charcoal	21,086	1,000	25,430	2,640	Chen and Wang, 1989
Yanjiagang	?	126.300	45.600	?	21,737	300	26,250	1,200	Wu and Poirier, 1995
Heilongtan	ZK2129	118.300	34.517	clay & charcoal	21,820	520	26,260	1,560	IA-CASS, 1991
Beijing (Wangfujing)	?	116.417	39.917	?	22,670	300	27,370	900	Li *et al.*, 1998
Xiachuan (Locality 1)	ZK417	112.033	35.450	charcoal	23,224	1,000	27,860	2,600	Chen and Wang, 1989
Zhoukoudian (Upper Cave)	OXA1248	115.917	39.683	bone	23,150	330	27,940	680	Lu, 1999: Table 4(1)
Xiaonanhai	ZK654	114.117	36.117	charcoal	23,419	500	28,310	1,200	Lu, 1999: Table 4(1)
Zhoukoudian (Upper Cave)	OXA1247	115.917	39.683	bone	23,700	350	28,630	900	Lu, 1999: Table 4(1)
Shuidonggou (Locality 2)	Beta 146358	106.504	38.297	charcoal	23,790	180	28,700	580	Madsen *et al.*, 2001
Miaohoushan	PV0363	124.167	41.233	fossil bone	23,880	570	28,820	1,300	IA-CASS, 1991
Xuetian	LZU-?	127.550	44.783	?	24,500	400	29,430	1,080	Fu, 2003
Shuangbuzi	?	105.957	35.307	clay	24,538	290	29,520	900	Xie, 1997
TX08	CAMS 93169	105.249	36.685	charcoal	24,760	220	29,820	560	Ji *et al.*, 2005
GY03	CAMS 93161&2	106.640	35.831	charcoal	25,228	766	29,960	1,480	Ji *et al.*, 2005
Tashuihe	ZK2599	113.200	35.700	bone	25,425	1,005	30,010	1,820	IA-CASS, 1992
TX03	CAMS 93167&8	105.675	36.656	charcoal	25,030	80	30,040	380	Ji *et al.*, 2005
Shuidonggou (Locality 1)	PV0317	106.333	38.100	carbonate	25,450	800	30,140	1,400	IA-CASS, 1991
Caisi	ZK0635	111.417	35.833	shell	25,650	800	30,290	1,340	IA-CASS, 1991
Yangsigouwan	PV0185	108.617	37.833	fossil bone	25,620	710	30,310	1,200	IA-CASS, 1991

(Continued)

Table 1. (Continued)

site	lab.#	lon.DD	lat.DD	material	^{14}C yr BP	+/−	Cal yr BP	+/−	reference
Shuidonggou (Locality 2)	Beta 134825	106.504	38.297	charcoal	25,650	160	30,580	360	Madsen *et al.*, 2001
Shuidonggou (Locality 2)	Beta 132983	106.504	38.297	charcoal	25,670	140	30,590	340	Madsen *et al.*, 2001
Mingyuegou	WB78-41	128.917	43.117	fossil bone	25,810	550	30,590	760	IA-CASS, 1991
Zhoukoudian (Upper Cave)	OXA2275	115.917	39.683	bone	25,700	360	30,600	540	Lu, 1999: Table 4(1)
Zhoujiayoufang	WB78-05	126.533	44.767	fossil wood	25,980	735	30,600	1,040	IA-CASS, 1991
Zalainuoer	PV0175	117.588	49.350	coprolite	25,940	1,300	30,710	2,740	IA-CASS, 1991
Zalainuoer	PV0220	117.583	49.350	fossil bone	26,240	800	30,860	1,140	IA-CASS, 1991
Changweigou	?	105.938	35.123	?	26,336	600	30,890	760	Xie, 1997
Dingcun	PV1064	111.417	35.933	shell	26,450	590	30,970	740	Lu, 1998
Shuidonggou (Locality 2)	Beta 146355	106.504	38.297	charcoal	26,310	170	30,990	260	Madsen *et al.*, 2001
Shuidonggou (Locality 2)	Beta 132982	106.504	38.297	charcoal	26,350	190	31,000	280	Madsen *et al.*, 2001
Zhoukoudian (Upper Cave)	OXA1246	115.917	39.683	bone	26,500	460	31,000	540	Lu, 1999: Table 4(1)
Shuidonggou (Locality 2)	Beta 134824	106.504	38.297	charcoal	26,830	200	31,230	200	Madsen *et al.*, 2001
Shuidonggou (Locality 2)	Beta 132984	106.504	38.297	ostrich shell	26,930	120	31,270	160	Madsen *et al.*, 2001
Zhoukoudian (Upper Cave)	OXA2274	115.917	39.683	bone	27,370	410	32,000	1,260	Lu, 1999: Table 4(1)
ZS08	Beta 210740	35.329	106.119	charcoal	27,730	150	32,074	976	*reported here*
Zhoukoudian (Upper Cave)	OXA2272	115.917	39.683	bone	27,500	380	32,090	1,280	Lu, 1999: Table 4(1)
Miaohoushan	PV0366	124.167	41.233	fossil bone	27,240	680	32,120	1,720	IA-CASS, 1991
Mingyuegou	WB78-43	128.917	43.117	fossil tooth	27,910	750	32,730	2,060	IA-CASS, 1991
Shidie	ZK2100	113.817	37.233	charred bone	27,920	1,175	32,930	2,700	IA-CASS, 1991
Zalainuoer	PV0172	117.583	49.350	charcoal	28,120	1,300	33,090	2,900	IA-CASS, 1991
Shiyu	ZK109-0	112.283	39.350	fossil bone	28,135	1,330	33,110	2,940	IA-CASS, 1991
Zhoukoudian (Upper Cave)	OXA2271	115.917	39.683	bone	28,680	460	33,450	1,900	Lu, 1999: Table 4(1)
Zhoujiayoufang	WB78-45	126.533	44.767	coprolite	28,910	1,220	33,630	2,940	IA-CASS, 1991
Guxiangtun	BK77022	126.517	45.700	charcoal	29,150	700	33,920	2,120	IA-CASS, 1991
Zhoukoudian (Upper Cave)	OXA2276	115.917	39.683	bone	29,100	520	34,040	1,680	Lu, 1999: Table 4(1)
Shuidonggou (Locality 2)	Beta 146357	106.504	38.297	charcoal	29,520	230	34,760	740	Madsen *et al.*, 2001
Shidie	ZK2006	113.817	37.233	bone	30,600	1,570	35,660	4,040	IA-CASS, 1991
Zhoujiayoufang	WB78-46	126.533	44.767	fossil bone	30,900	910	36,070	1,740	IA-CASS, 1991
Gutougou	LZU-??	104.750	34.783	clay	32,844	500	38,090	1,560	Xie *et al.*, 1987
Zhoukoudian (Upper Cave)	OXA190	115.917	39.683	bone	32,600	2,000	38,130	4,520	Lu, 1999: Table 4(1)
Zalainuoer	PV0170	117.583	49.350	coprolite	32,810	1,700	38,440	3,980	IA-CASS, 1991
Zhoukoudian (Upper Cave)	OXA2277	115.917	39.683	bone	33,200	820	38,810	2,760	Lu, 1999: Table 4(1)
Zhoukoudian (Upper Cave)	OXA2773	115.917	39.683	bone	33,460	850	39,080	3,000	Lu, 1999: Table 4(1)
Mingyuegou	WB78-42	128.917	43.117	fossil tooth	34,370	1,850	39,430	3,800	IA-CASS, 1991
Xiachuan (Fuyuhe)	ZK638	112.033	35.450	charcoal	35,177	3,500	39,540	6,200	Chen and Wang, 1989
Fajiagouwan	PV0177(2)	108.617	37.833	charcoal	35,340	1,900	40,060	3,740	IA-CASS, 1991
Temple Canyon 1	Beta 161632	105.800	38.700	carbonate	41,070	890	44,690	1,660	Bettinger *et al.*, 2003

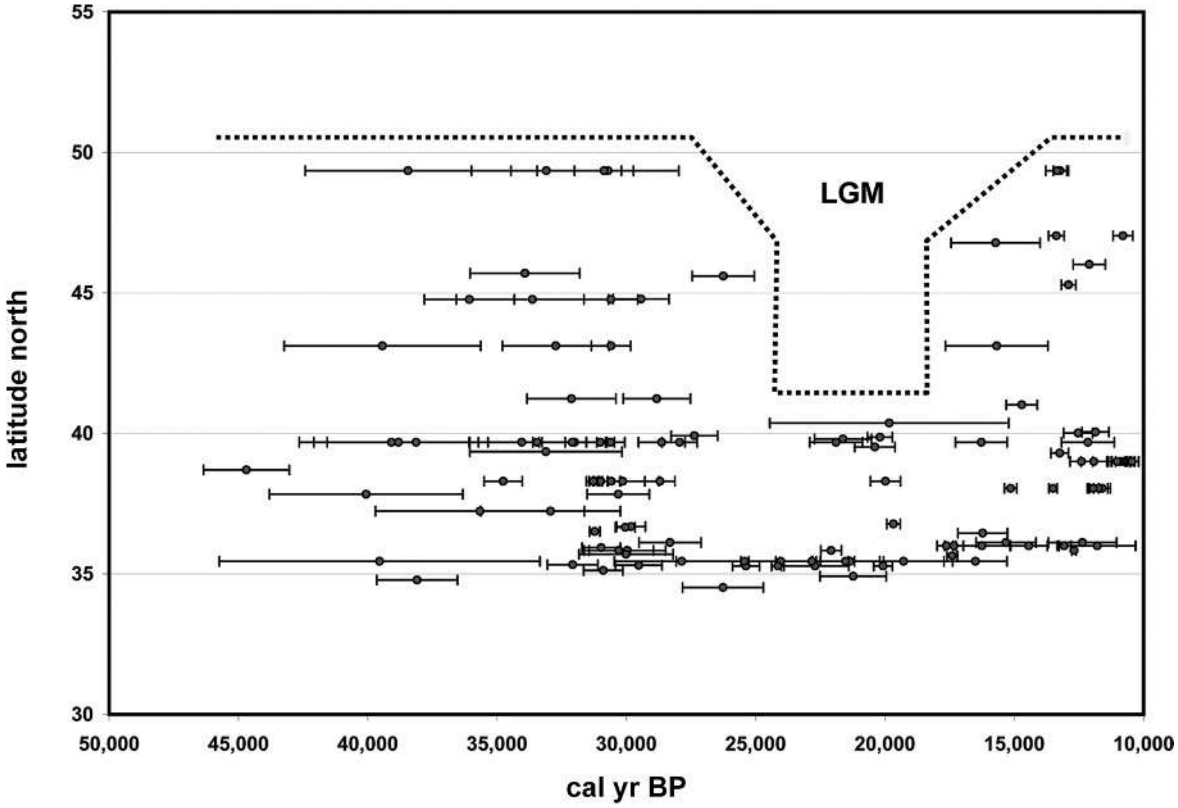

Fig. 1. Radiocarbon data from Paleolithic north China (n = 116) plotted as a function of latitude. This illustrates that north China was depopulated above 41° north during the last glacial maximum (24.0–18.0 ka). Diamonds represent the 2σ mid-point of each calibrated estimate, while the circles represent the 2σ range.

associated errors in a graphic representation of archeological occupation in calendar years. Peaks in the calibrated radiocarbon probability distribution represent clusters of calibrated age estimates. Following the general logic outlined by Rick (1987), other researchers have used cumulative probability distributions of calibrated radiocarbon dates as proxies for human population dynamics (e.g., Gamble *et al.*, 2004; Surovell *et al.*, 2005). Here, we prefer to use the probability distribution as a measure of archeological visibility and suggest this visibility is a result of occupation intensity (Figure 3). Essentially, more sites are sampled and more dates collected from periods when hunter-gatherers occupy fewer places for longer periods of time. Conversely, when human foragers are highly mobile, occupation intensity should be low, as population aggregation is limited and human activity more evenly distributed across the landscape. Therefore, peaks in the probability distribution of calibrated radiocarbon dates represent periods of reduced mobility, and we expect this reduction in mobility to reflect declining access to increasingly limited resources.

Assuming that generalized resource abundance is a function of regional humidity and temperature, we look to continuous, high-resolution paleoenvironmental records from East Asia, such as the Hulu Cave speleothem sequence, as a proxy for terrestrial productivity.

Fluctuations in the oxygen isotope composition of speleothem calcite at Hulu Cave in southeast China record tradeoffs between the relative contributions of summer and winter precipitation and therefore constitute an integrated record of monsoon intensity over the East Asian landmass (Wang *et al.*, 2001; Yuan *et al.*, 2004). When the East Asian Pacific monsoon is dominant, summer rains are strong and $\delta^{18}O$ values lower, indicating heavy precipitation transport from a proximate tropical source. Higher $\delta^{18}O$ values suggest long-distance transport of water vapor from the northwest, indicative of a stronger winter monsoon and perhaps reduced annual precipitation. Comparative studies suggest that warmer hemispheric temperature, as shown in Greenland ice core records, corresponds to greater summer monsoon intensity (Wang *et al.*, 2001) and that precipitation from tropical sources is low during glacial periods, even in southeast China (Yuan *et al.*, 2004).

Visual comparison of the radiocarbon probability distribution and the Hulu Cave record suggests that occupation intensity is highest, and therefore human mobility is reduced, during periods dominated by the cold/dry winter monsoon (Figure 3). However, a basic linear regression of Hulu Cave speleothem $\delta^{18}O$ values against the CalPal cumulative probability distribution shows very weak correlation between climate and occupation intensity

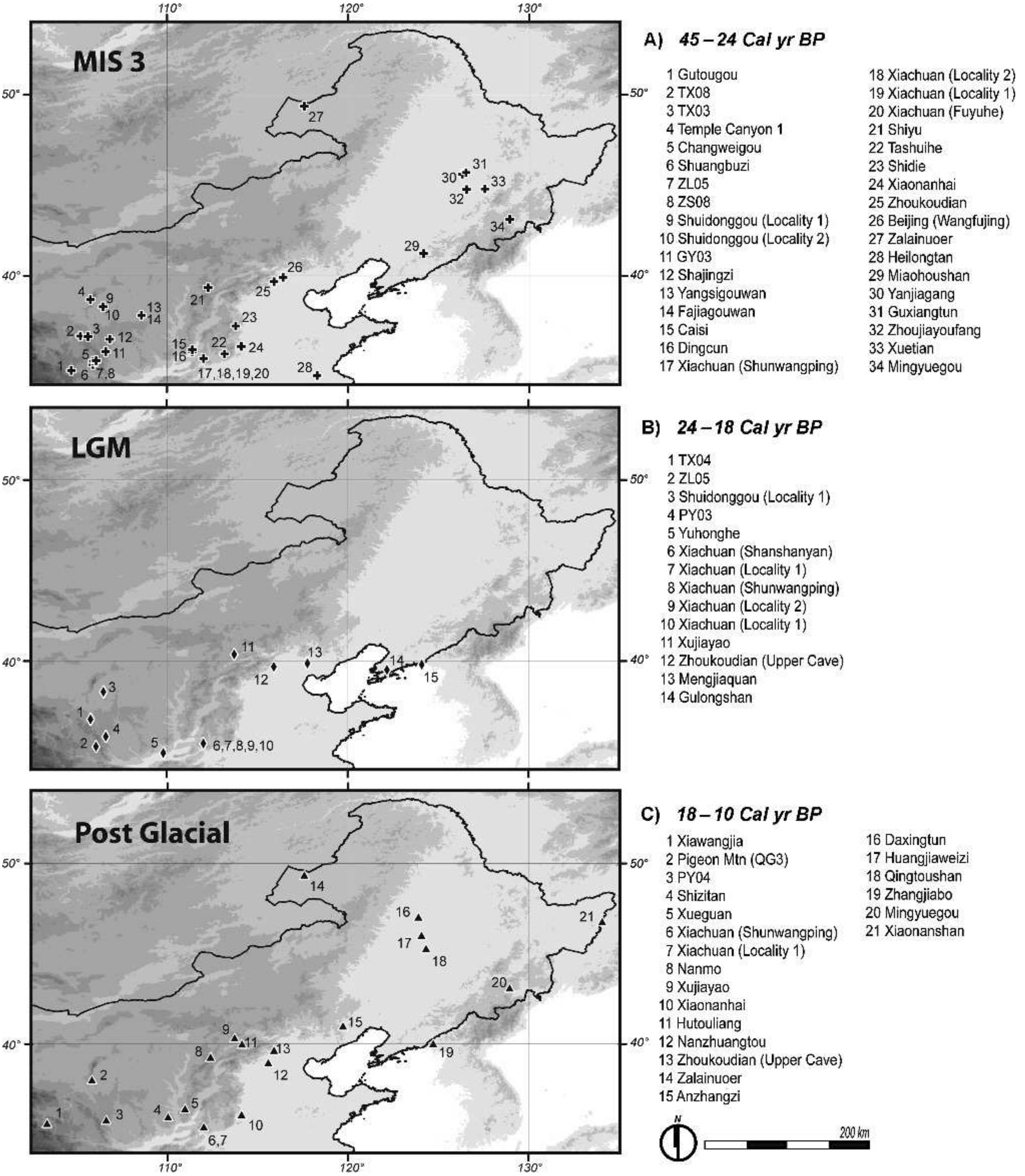

Fig. 2. Late Pleistocene archeological sites in northern China. Sites are assigned to one of the three periods on the basis of calibrated radiocarbon age ranges (Table 1): (A) MIS3 45.0–24.0 ka; (B) LGM 24.0–18.0 ka; (C) post-glacial 18.0–10.0 ka. Most of northeast China is depopulated during the LGM.

($R^2 = 0.0913$), suggesting that most variations around the environmental mean are insufficient to effect significant changes in human behavior. There is, however, a very strong correlation between occupation intensity and extreme environmental change, defined as $\delta^{18}O$ values 1.5 standard deviations above and below the mean $\delta^{18}O$ value between 45 and 10 ka. Figure 4 illustrates this relationship. Hulu Cave isotopic values greater than 1.5 standard deviations

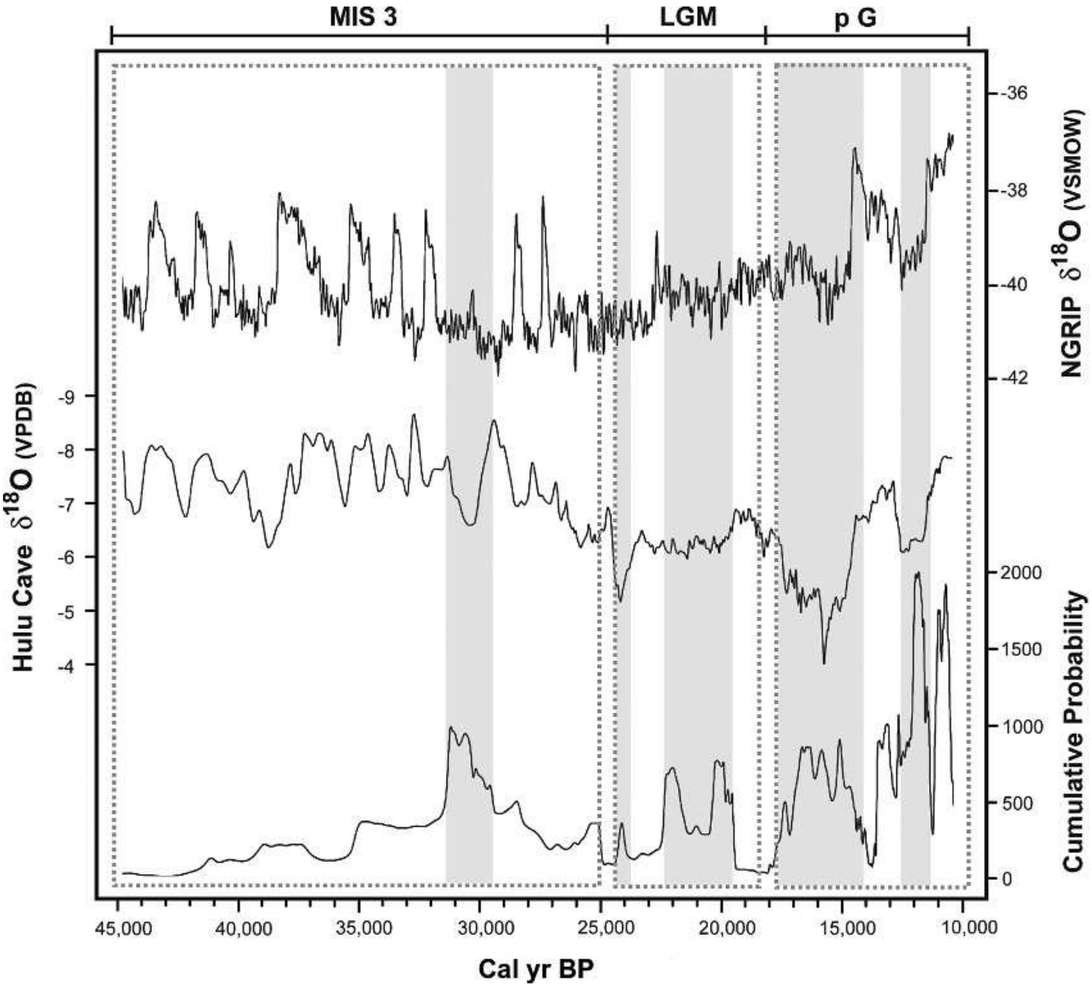

Fig. 3. Graphic comparison of human occupation intensity against climate. The bottom curve represents occupation intensity across northern China as a function of the cumulative probability of radiocarbon age estimates. The middle curve is a proxy for monsoon intensity in south China (Wang et al., 2004). Higher $\delta^{18}O$ values indicate strong winter monsoons (cold/dry); lower values indicate stronger summer monsoons (warm/wet). The upper curve represents hemispheric changes in precipitation and temperature recorded in Greenland ice (NGRIP, 2004). Higher $\delta^{18}O$ values indicate warmer temperatures and higher humidity. Shaded bars identify visual correlations between occupation intensity and climate.

from the mean correspond with high occupation intensity while isotopic values 1.5 standard deviations below the mean correspond with low occupation intensity. One-way analysis of variance confirms that occupation intensity is consistently higher during cold/dry periods dominated by the winter monsoon than during periods dominated by the warm/wet summer monsoon ($F = 167.4$; $P = 0.000$). This suggests that the range of Paleolithic human foraging behaviors adapted to marginal environments like those of Pleistocene northeast Asia are stable in all but the most extreme of climatic anomalies. During such extremes, we see significant modifications to human settlement–subsistence patterns reflected in the distribution of calibrated radiocarbon probabilities from northern China.

Explanation of this pattern rests on understanding the interplay between resource distribution and human mobility. Recurrent dominance of the high-precipitation summer monsoon system during the MIS3 interstadials kept lake levels high (Chen and Bowler, 1986; Pachur *et al*., 1995; Komatsu *et al*., 2001) and stabilized the expansive steppe and grasslands that supported large-bodied terrestrial mammal populations across northeast Asia. The relative ubiquity of subsistence resources during these warm/wet intervals enabled Paleolithic hunter-gatherers to move freely between lake margins, grasslands, and animal migration routes to intercept the seasonal movements of large, seasonally mobile ungulate herds. As subsistence productivity declined in one area, human hunters moved easily into adjoining areas to capitalize on the rich biomass of the previously undisturbed local environment. The combination of high environmental productivity and low human population density during the warm/wet intervals of MIS3 meant that subsistence risks associated with movement into adjacent areas were relatively low. This enabled small foraging groups to relocate both

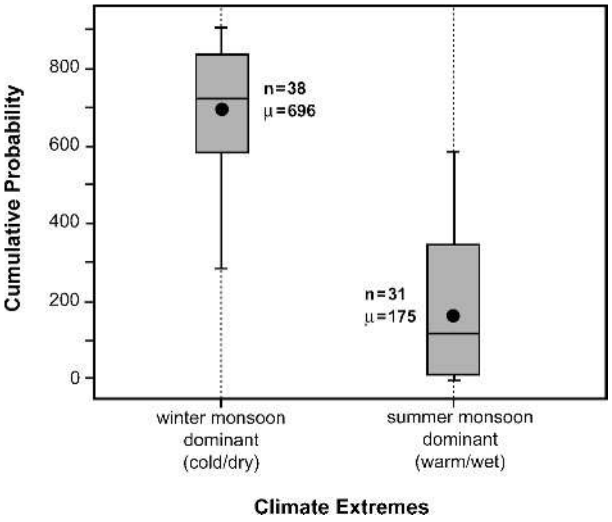

Fig. 4. Occupation intensity by environmental extreme. Analysis of variance demonstrates that two environmental extremes (as determined by the Hulu Cave $\delta^{18}O$ monsoon intensity record) correspond to significantly different human settlement patterns: Occupation intensity, a measure of population concentration, is more pronounced during cold/dry intervals, whereas warm/wet intervals correspond to high mobility.

their foraging range and their residential base opportunistically, creating an irregular "random walk" pattern of movement about the landscape (see Brantingham *et al.*, 2003; Brantingham, 2003; Brantingham, 2006).

Simulation studies suggest this "random walk" pattern becomes increasingly difficult for human foragers to sustain as the total productivity of the landscape declines and resources become increasingly concentrated in fewer locations separated by greater distances (Brantingham *et al.*, 2003). With the onset of the LGM, freshwater bodies in northeast Asia retreat, become saline, or disappear completely (Pachur *et al.*, 1995; Owen *et al.*, 1997; Zheng *et al.*, 1998; Yang *et al.*, 2004), while sand and gravel deserts expand dramatically at the expense of grasslands and steppic vegetation (Feng *et al.*, 1998; Sun *et al.*, 1998; Yu *et al.*, 2000; Xie *et al.*, 2002; Zhou *et al.*, 2002). The resulting "patchy" distribution of freshwater resources effectively constrains the distribution of plants and animals dependent upon them. Here, the implications for human foraging groups are profound: long-distance movement between rare and perhaps unpredictable fresh water sources becomes increasingly hazardous. Long-distance movements are unlikely because the risks of resource shortfall are high and the costs of movement are great.

In this situation, foraging groups become increasingly tethered to the few remaining areas capable of supporting consistent plant and animal survival. While high residential mobility was the easiest solution to local resource depression during the recurrent warm/wet intervals of the MIS3, survival during cold/dry intervals required reduced residential mobility and alternative methods of reducing the risks of subsistence shortfall. Ultimately, human foragers were forced to develop novel adaptive strategies to contend with the unprecedented, extreme, and prolonged environmental restrictions of the LGM.

4. Cultural Evolution and the LGM

4.1 The Archeological Record of Northeast Asia

Our analysis of radiocarbon data from across northern China suggests that while human settlement patterns did change in response to environmental deterioration, the region was not abandoned entirely. Similarly, radiocarbon data from Siberia and the Russian Far East demonstrate that other regions of northeast Asia were not abandoned during the LGM (Kuzmin and Keates, 2005). Furthermore, it seems that neither the Korean Peninsula nor the Japanese archipelago were abandoned outright during the LGM (Bae and Kim, 2003; Ikawa-Smith, 2004; Nakazawa *et al.*, 2005).

It is clear, however, that following the LGM a new adaptive technology built around the production of microblades spread rapidly in China, Siberia, Korea, and Japan. The seemingly instantaneous appearance of microblades across the whole of northeast Asia has been attributed to the recolonization of landscapes left vacant by regional population extirpations brought on by the LGM (Goebel, 1999; Goebel, 2002; Goebel, 2004; Brantingham *et al.*, 2004b).

Despite considerable attention (e.g., Chard, 1974; Chen, 1984; Gai, 1985; Tang and Gai, 1986), the origins of northeast Asian microblade technology remain unclear (Lu, 1998; Cohen, 2003). The most liberal interpretations of the archeological evidence for microblade technology suggest that they were an uncommon but recurrent feature of Late Pleistocene adaptations during the MIS3, often overlapping with the EUP or even the Early Paleolithic in northern China, between 31 and 25 ka (Chen and Wang, 1989; Lu, 1998), and in Siberia between 30 and 25 ka (Derevianko *et al.*, 1998). The emergence of microblade industries in Japanese Hokkaido (Nakazawa *et al.*, 2005) and southern Korea (Bae and Kim, 2003; Ikawa-Smith, 2004) by 24 ka, further suggests that a single origin and subsequent diffusion of this technology is unlikely (cf. Chen, 1984; cf. Chen and Wang, 1989). Rather than searching for single origins, archeologists should be looking to each of these early cases for similarities that might underscore the adaptive benefits of microblade technology (Elston and Brantingham, 2002). For each of these early cases, microblade technology should be considered an outgrowth of Paleolithic industries in existence prior to the LGM (see Brantingham *et al.*, this volume).

In northern China, the presence of small microblade-like, bipolar bladelets at Shuidonggou-2 suggests a potential technological substrate from which a classic microblade industry may have emerged (Madsen *et al.*, 2001; Brantingham *et al.*, 2004a; Brantingham *et al.*, 2004b). Numerous archeological examples from other parts of northeast Asia confirm the use of microblades as inserts in composite tools (Chard, 1974; Lu, 1998; Derevianko *et al*., 1998), therefore, the critical innovation required for the emergence of microblade technology is a tool form in which small, replaceable, sharp stone flakes may be inserted in hafts or fore-shafts made of wood or bone. If the EUP blade forms generated through prepared-core technology at Shuidonggou were used as inserts in composite tools, then perhaps other flake and blade tools might be easily incorporated as the need arose. The essential points about the assemblage at Shuidonggou-2 are first, the production of small, retouched microblade-like bipolar bladelets co-occurred with production of classic EUP tool forms, suggesting cultural continuity between the two technological adaptations, and second, composite tool technologies were in place prior to the LGM.

4.2 Archeological Investigations at Zhuang Lang 5

The undisturbed stratigraphic sequence of the ZL05 exposure provided an ideal setting for two angles of research: (1) to examine the environmental context of human occupation in the western Loess Plateau during the LGM; and (2) to assess the potential for cultural continuity between the earlier EUP complex at Shuidonggou and the later, apparently local adaptations at ZL05 in the western Loess Plateau. In 2004, we returned to collect a continuous paleoenvironmental record from the ZL05 loess profile and to excavate sufficient cultural material to characterize these local human adaptations.

The ZL05 site (originally "ZL005") was named for the nearby city of Zhuang Lang, in southern Gansu Province, west of the Liu Pan Mountains. The site has also been called "Sumiaoyuantou" (Ji *et al*., 2005) because of its proximity to a previously recorded, but unstudied site with the same name.

ZL05 was discovered on a pedestrian survey of the Shui Luo River and its tributary, the Bei Shui Luo River. High above the river, on a promontory that marks the confluence of the two rivers sits a large Late Neolithic site. Immediately below this is a broad flat terrace that planes roughly 10 m above the north side of the modern Bei Shui Luo riverbed (Figure 5). The river action that cut this terrace exposed the ZL05 site and an extensive, previously un-cut section of aeolian Pleistocene loess. While the top 2 m of the terrace section show evidence of periodic Late Neolithic and dynastic disturbance, most of the section is pristine. The dominant archeological component rests, suspended in fine-grained Malan loess, approximately 1.5 m above the surface of the Bei Shui Luo flood plain (Figure 6: Component X). That all of the artifacts are un-rolled and in-place, and no other evidence of fluvial re-deposition such as gravel stringers or sandy deposits were found in or around the cultural components, confirms that the archeological assemblage was neither disturbed nor deposited by fluvial action. By all appearances, this site was occupied briefly and buried rapidly by airborne deposition.

The site was not excavated exhaustively, but rather sampled horizontally from its southern face. All culture-bearing deposits were wet-screened with 3 mm mesh and several samples were subjected to water flotation with an Ankara-style flotation tank at Lanzhou University. With the exception of two carbonized *Chenopodiaceae* fragments in "Component X", flotation produced very little charred material indicative of in situ anthropogenic burning. At

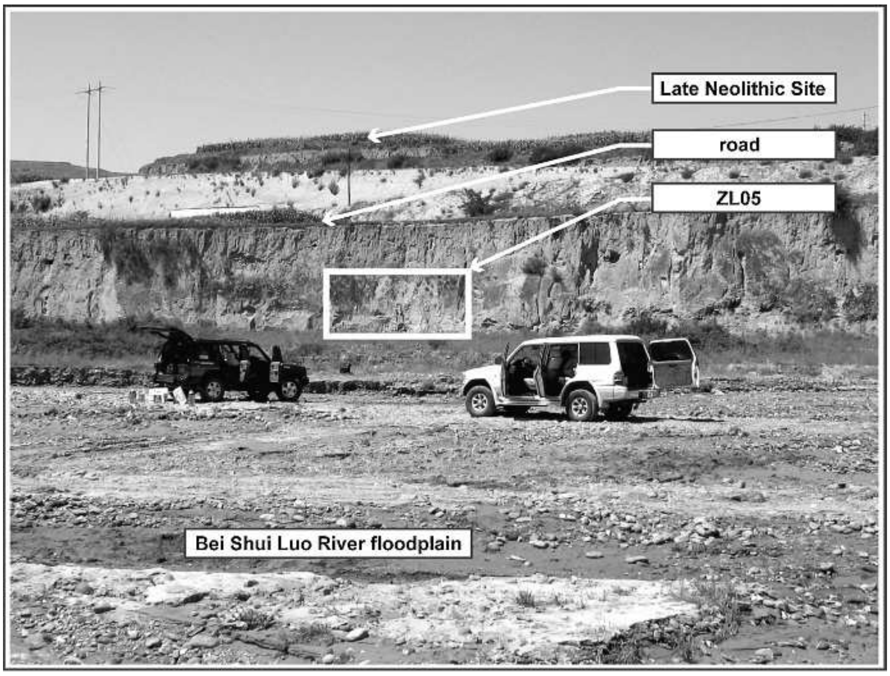

Fig. 5. Looking north to the south-facing profile at ZL05 across the Bei Shui Luo River. (Photo by D.B. Madsen.)

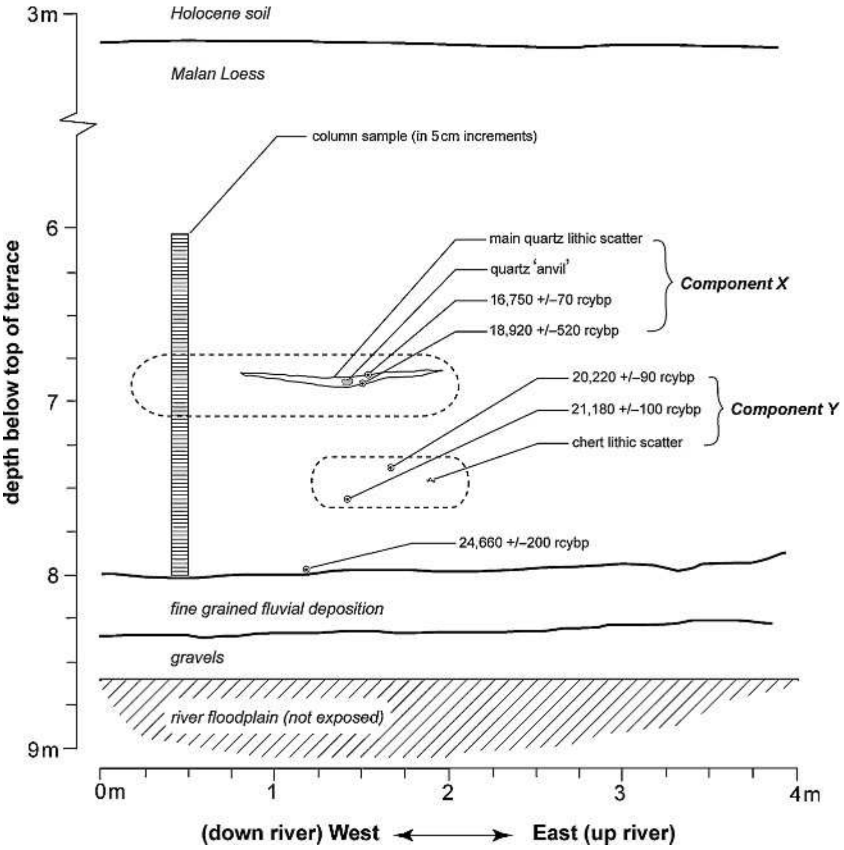

Fig. 6. The ZL05 excavation profile

this point, it is impossible to know whether these seeds represent local processing and subsequent burning of small-seed bearing plants or if they are the product of local range fires. If further excavation were to corroborate the former, ZL05 would represent one of the earliest known examples of small-seed subsistence in China and, for that matter, anywhere in the world.

The dominant ZL05 cultural component represents a relatively isolated event of lithic reduction (Figure 6: Component X). The centerpiece of the component is a robust and pitted quartz slab surrounded by broken quartz core fragments, and thousands of small pieces of quartz debitage, distributed densely up to a meter away from the center of the deposit. The slab itself is an anvil upon which numerous massive crystalline quartz cobbles, presumably collected from the nearby riverbed, were battered through bipolar reduction to generate expedient flakes and small geometric lithic shards (Table 2). No retouched or classically formal tools were recovered from this assemblage, but two blade-like flakes emerged, reminiscent of the expedient bipolar blades recovered from Hearth 2 at Shuidonggou, Locality 2 (Brantingham *et al.*, 2004a). Two radiocarbon estimates anchor the upper ZL05 lithic component to the LGM, between 24.0 and 19.7 ka (Figure 6).

The appearance of additional, temporally distinct cultural material at other points in the section suggests that this location was visited repeatedly during the Late Pleistocene. Evidence for the small-scale reduction of chert, roughly 45 cm below the main lens of occupation (Figure 6: Component Y), dates between 25.9 and 23.9 ka. Additionally, several isolated but undated chipped stone implements were found scattered throughout the Malan loess.

Geologically, the section is comprised of five distinct depositional events (Figure 7). The uppermost layers are modern cultivated soils and disturbed Holocene paleosols. The layer in which the cultural deposits rest is massive, friable, Pleistocene loess, generally consistent with Malan loess deposits found in other regions of the Loess Plateau (e.g., Chen *et al.*, 1997). This deep Malan loess deposit sits atop non-compact, granular, reddish sand, interleaved by fine, yellow sand. Below this are poorly sorted, rounded gravels, indicative of high-energy alluvial deposition. The contact between the aeolian Malan loess and the preceding alluvial deposition dates between 29.3 and 27.8 ka (Ji *et al.*, 2005; Bettinger *et al.*, n.d.).

Column sampling of the Malan loess at ZL05 in 5-cm increments enabled a high-resolution paleoenvironmental sequence for the period surrounding the primary occupation of the site (Figures 6 and 7). Specifically, two proxy markers of monsoon variability, Magnetic Susceptibility and Grain Size Distribution Analysis, suggest a pattern consistent with the loess–paleosol sequence established elsewhere in the western Loess Plateau (Chen *et al.*, 1997). Likewise, the

Table 2. Lithics from ZL05. Size sorting (following Henry et al., 1976; Ahler, 1989) with a stack of nested geological test sieves yields a size distribution to define bipolar reduction of massive crystalline quartz cobbles (Component X). Component Y is too small (n = 5) to determine reduction strategy from a size distribution. "Other" represents a compilation of scattered lithics, found embedded throughout the profile, and "surface" represents surface collections directly below the ZL05 section.

	>10mm	10–5mm	5–2.5 mm	<2.5 mm	blade	core	core frag	anvil	N
component X	203	537	1,241	247	2	7	11	1	2,249
component Y	0	2	3	0	0	0	0	0	5
other	0	3	14	0	1	0	0	0	18
surface	27	8	3	1	0	0	7	0	46
total	230	550	1,261	248	3	7	18	1	2,318

ZL05 sequence is generally consistent with the Hulu Cave record which tracks summer monsoon intensity as a record of $\delta^{18}O$ fluctuations in speleothem calcite (Wang *et al.*, 2001; Yuan *et al.*, 2004). High-energy fluvial action at the base of the ZL05 section corresponds to a pronounced peak in the Hulu Cave speleothem record indicative of summer monsoon dominance. This peak has also been correlated with Dansgaard–Oeschger warming event number 4 (Wang *et al.*, 2001: 2346), which marks the beginning of a steady decline into the Last Glacial.

Soil formation, often measured by magnetic susceptibility, implies high precipitation and is an established proxy for summer monsoon intensity in the Loess Plateau (An *et al.*, 1991). The Xlf magnetic susceptibility record from the ZL05 section demonstrates pronounced soil formation for the interval between 29.0 and 24.0 ka, but declines immediately thereafter as summer monsoon precipitation decreased in concert with global patterns of environmental change characteristic of the long steady slide into the LGM.

Increases in mean and median grain-size, relocated by wind action from the expanding deserts northwest of the Loess Plateau, are characteristic of loess deposition records during the LGM (Derbyshire *et al.*, 1998; Kohfeld and Harrison, 2003) and point to the increasing dominance of the winter monsoon system, perhaps governed by the interaction between the Siberian–Mongolian high pressure and Aleutian low pressure systems (Ding *et al.*, 1992; Chen *et al.*, 1997). At ZL05, the increased median size of the windborne dust particles confirms the strength of the winter monsoon during the LGM. Lastly, this high-resolution

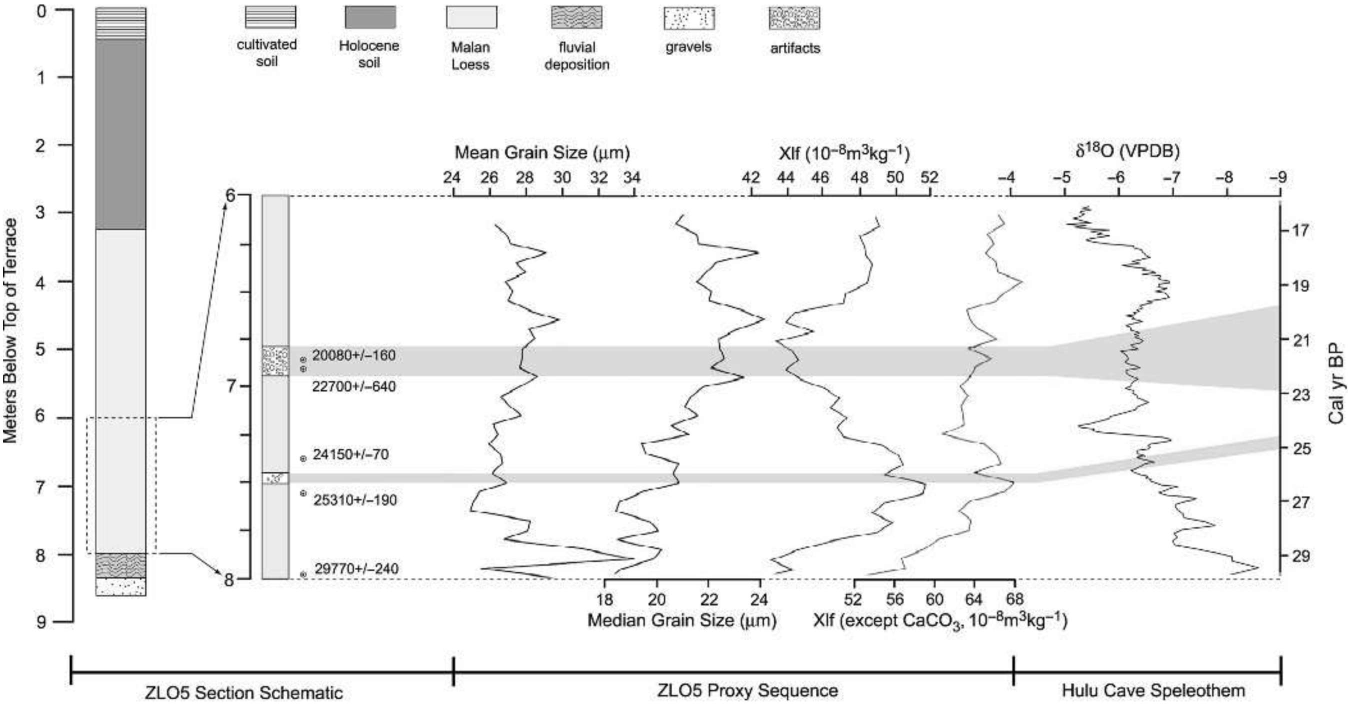

Fig. 7. Geological deposition and environmental proxies from ZL05. The Hulu Cave proxy for monsoon intensity is provided at right for rough comparison.

sampling at ZL05 illustrates the punctuated variability of the winter/summer monsoon trade-offs during the last interglacial–glacial cycle.

5. Raw Materials, Paleolithic Tool Technology, and Human Mobility

To interpret the archeological record of the western Loess Plateau we combine our analysis of hunter-gatherer mobility based on radiocarbon data, with basic archeological patterns of stone raw material use throughout the region. Essentially, the frequency of specific raw materials in archeological assemblages reveals how people acquire them.

For hunter-gatherers, stone raw materials are acquired either by trade or by direct access. Given the low population density of Pleistocene northeast Asia and the volatility of environmental change during MIS3, direct access is perhaps the best explanation for raw material acquisition for much of the Pleistocene.

One of us (Brantingham, 2003) has argued that the diversity of stone raw materials in an archeological assemblage results from: (1) how much toolstone an individual can carry; and (2) how rapidly the mobile toolkit changes as local materials are incorporated to replace exotic materials carried from greater distances. The simulations in this model are based upon a "random walk" foraging pattern, similar to that proposed for the EUP foragers of the MIS3 interglacial (Brantingham *et al.*, 2003). In this scenario, hunter-gatherer mobility patterns are assumed to operate without regard to raw material availability. Rather, hunter-gatherer movement is determined by local subsistence productivity. Hunter-gatherers move from one foraging patch to the next in response to resource depression, generating a seemingly random pattern of movement about the landscape. If movement is determined by access to subsistence resources, and not lithic resources, then we should expect to see hunting technologies capable of incorporating a wide range of local raw materials, regardless of the limitations of the material. If this "neutral model" is correct, the archeological assemblages of highly mobile, random walk hunter-gatherers should always be dominated by local materials and the manner of stone tool use and manufacture should reflect the local character of the raw materials. This simple, deterministic relationship has been demonstrated with both archeological and ethnographic data (Andrefsky, 1994).

The basic implications of the neutral model, that raw material availability has little effect on the migratory patterns of human foragers, suggest that highly mobile, random walk foragers transfer exotic raw materials, perhaps over great distances, but not with any regularity. Whenever the random walk foraging pattern exists, the proportion of exotic raw materials in the archeological assemblage should be low, but potentially visible. Furthermore, as the random walk pattern is curtailed by environmental circumscription, access to exotic raw materials declines steeply and their archeological representation should be negligible.

If exotic materials carried in the mobile tool kit decline exponentially with increasing distance from the source of the materials (Brantingham, 2003), the technological adaptations underwriting random walk hunter-gatherer subsistence strategies must be flexible enough to incorporate a wide range of raw materials. Strategies built upon rigid, prepared-core technologies, such as flat-faced core and blade reduction (a defining feature of the EUP), biface technology, or microblades, will not survive the random walk pattern when hunter-gatherers move into regions bereft of suitable raw materials. Therefore, we do not expect to see much of the typical EUP technology in the western Loess Plateau where find-grained cryptocrystalline raw materials, such as those used at Shuidonggou, are rare or non-existent. For a random-walk foraging pattern geared toward the pursuit of shifting resource abundance, as was characteristic of the last interstadial, to survive and persist, it must be supported by a highly flexible technological adaptation.

The production of blades during the EUP suggests a composite tool technology wherein stone tools, including levallois-style blades and points, are set in some combination of shafts, foreshafts and other hafting elements to create implements suitable for large game hunting and butchering. These hafts and handles, presumably made from wood or bone, are thus the defining feature of the EUP and provide a flexible, technological substrate into which locally adaptive modifications might be incorporated. As hunter-gatherers moved into landscapes devoid of lithic raw materials suitable for EUP prepared-core blade, flake, and point manufacture, they developed alternative methods of stone tool production and adjusted these new, and perhaps smaller, lithic insets to suit the pre-existing composite weaponry system. This pattern is visible at ZL05 in Component X, where expedient, bipolar reduction of massive, crystalline quartz cobbles produced thousands of small lithic shards.

The ZL05 lithic data (Table 2) demonstrate that reduction of an individual cobble yields (minimally) 124 small fragments, and the predominant size of the debitage (5–2.5 mm) fits within the size range of truncated microblades. Presumably, the choice pieces of quartz were removed by the toolmaker for inserts in composite armatures. Alternatively, extensive bipolar reduction generated tool blanks that were removed for subsequent modification. The local abundance of quartz cobbles and the high volume of manufacturing debris suggest that raw material conservation was not imperative. Here, the costs of acquiring only a few suitable tool blanks by reducing a large number of locally abundant raw materials are low in comparison to acquisition and curation of higher-quality, exotic raw materials.

6. Hunter-Gatherer Occupation of the Western Loess Plateau

Radiocarbon determinations from TX08 and TX03 in the northern portion of the western Loess Plateau, ZS08 in the upper reaches of the Shui Luo River basin and GY03 in the eastern foothills of the Liu Pan Mountains are coeval with those at Shuidonggou (Table 1; Figure 8). In each of these cases, the lithic assemblages are comprised of rough stone tools, manufactured from massive, crystalline quartz cobbles with hard hammer and bipolar percussion (Ji *et al.*, 2005; Bettinger *et al.*, n.d.). While these sites are contemporaneous with the EUP assemblages at Shuidonggou, they do not conform to the classic expectations of the EUP techno-complex. The temporal and spatial proximity to Shuidonggou led Bettinger *et al.*, (n.d.) to classify the assemblages from these sites as the *Tong Xin* facies of the north China EUP. It seems clear that the assemblages from each of these sites represent adaptations to local resources, implying that regular access to higher-quality exotic materials was exceedingly costly, or at least rare enough to be relatively invisible archeologically. This local focus coincides with a pronounced cold/dry interval centered around 30.0 ka (Figure 3), suggesting reduced mobility.

However, at this point it would be premature to rule out a shared ancestry with the classic EUP adaptations at Shuidonggou. Recent archeological survey data from Ningxia Province, east and north of the Liu Pan Mountains along the current boundary of the desert–loess transition zone, demonstrate that an EUP blade technology similar to that at Shuidonggou exists over a much greater area than previously supposed (Gao *et al.*, 2004). Nevertheless, this technology does not penetrate into the higher elevation zones of the western Loess Plateau. Additional data from stratified

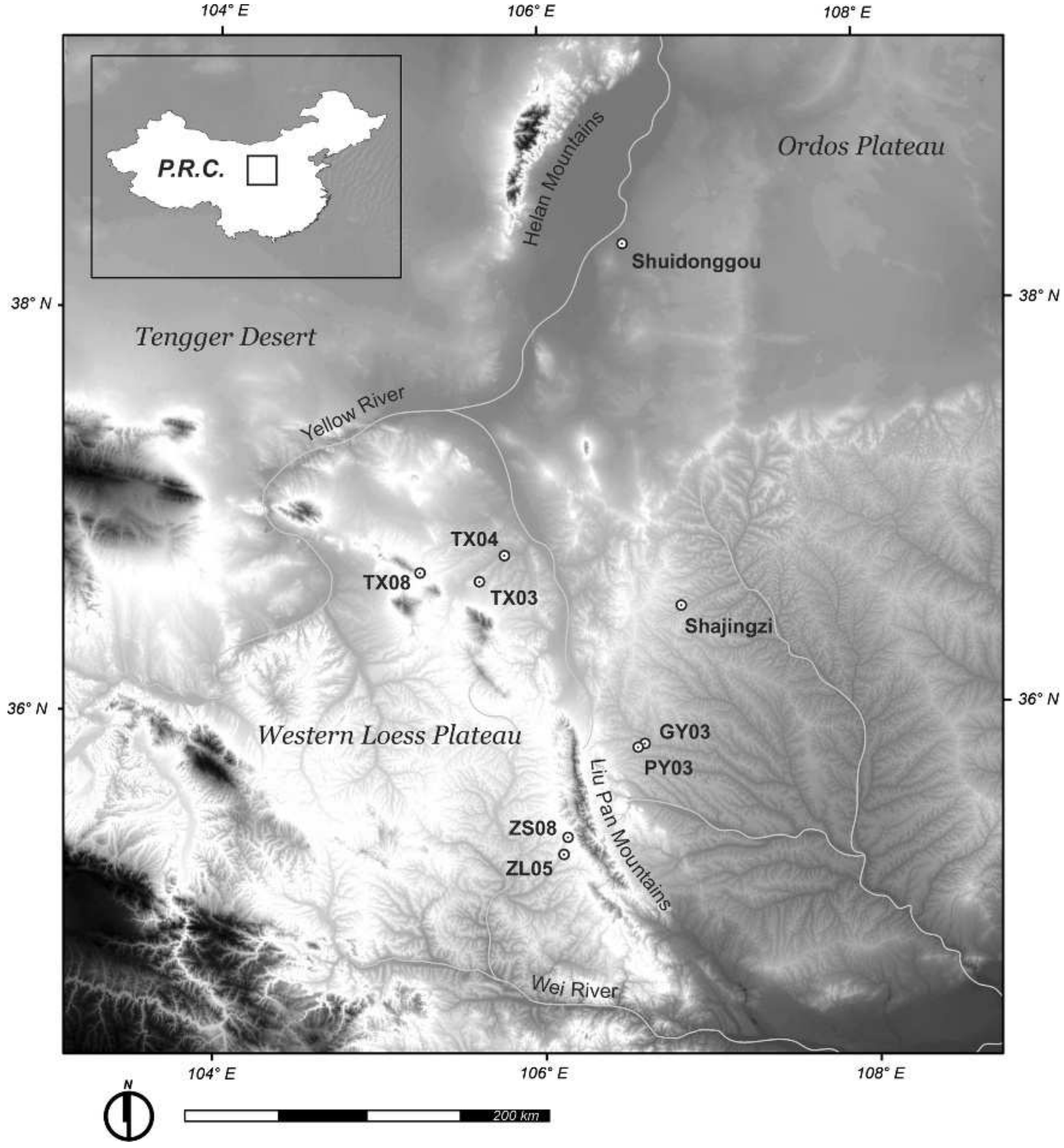

Fig. 8. Recently dated Paleolithic sites from the western Loess Plateau and surrounding regions.

archeological sites along the desert–loess boundary, specifically in Ningxia Province are necessary to clarify the nature of human mobility during this interval and to better establish the cultural connections between the *Tong Xin* EUP in the western Loess Plateau and the classic EUP adaptations further north.

At ZL05, the earliest evidence for temporary human occupation (Figure 6: Component Y) corresponds to a period dominated by the high-precipitation regime of the Pacific summer monsoon. That the cultural assemblage here is comprised of stone tool manufacturing debris made from non-local chert suggests the early inhabitants of this river margin were relatively mobile and carried their preferred toolstone with them over great distances as they went about their foraging rounds. In contrast, the proprietors of the later and much larger deposit of tool manufacturing debris (Figure 6: Component X) focused their attention on the highly abundant, but low quality, local quartz. The fracture mechanics of massive, crystalline quartz are irregular and unpredictable, making it far less optimal for prepared-core reduction technology than other raw materials such as cert, jasper, silicified limestone, or even quartzite (see Seong, 2004, for discussion and summary of vein quartz fracture mechanics). However, it is clear from the upper ZL05 component that local hunter-gatherers had little interest in raw-material conservation, choosing instead to batter the local materials intensively with hammer-and-anvil percussion until the desired flakes or shards were generated. The intensive and wasteful use of highly abundant, local raw materials suggests a pattern of reduced mobility during the cold, arid LGM.

Here, we incite the environmental parameters of range contraction put forth in the preceding sections. During MIS3 the migratory range of human foraging groups was consistently expanding and contracting in response to high-amplitude, long-term climate fluctuations characterized by the Dansgaard–Oeschger cycles. We have suggested that mild periods characterized by heavier summer rainfall and reduced winter dust storms facilitated high mobility among human foraging groups. It was during these intervals that the EUP expanded slowly by way of human migration across northeast Asia. This gradual pace is evident in the 10,000–15,000 year time lag between the initial appearance of EUP technology in Siberia and the later appearance of it at Shuidonggou in northern China (Brantingham *et al.*, 2001; Madsen *et al.*, 2001; Brantingham *et al.*, 2004a). Conversely, during the periods dominated by the cold/dry winter monsoon, hunter-gatherers were tethered to concentrated yet disparate and unpredictable resource patches, making long-distance movement between them much less feasible. Recurrence of these punctuated cold/dry intervals during MIS3 inhibited the random walk migration pattern of human foragers thereby limiting the rate of EUP cultural expansion.

At ZL05, the later, and much larger, "Component X" appears during a pronounced cold/dry interval, generally described as the LGM. Here, the expedient use of local raw materials seems to confirm the circumscribed range of hunter-gatherer groups occupying the Shui Luo River basin in the western Loess Plateau.

While microblade technology is a recurrent feature of the north China Upper Paleolithic, it is virtually unknown in the western Loess Plateau. This is due to the absence of suitable raw materials in the area and to the circumscribed nature of Paleolithic foraging strategies in the western Loess Plateau. True microblades, however, are evident north of the Yellow River along the southern limits of the Helan Mountains at Pigeon Mountain by 15.1 ka (Elston *et al.*, 1997) and at PY03 on the eastern slope of the Liu Pan Mountains by 22.1 ka (Bettinger *et al.*, 2003). At Pigeon Mountain and perhaps at Shuidonggou, raw materials suitable for microblade production are locally available. At PY03, a single, heavily reduced microblade core suggests either importation from adjacent regions or thorough reduction of a rare local resource. In each of these locations, the use of small, linear blades removed from prepared wedge, prismatic, or boat-shaped cores represents the addition of a distinct lithic reduction strategy to a pre-existing composite weaponry system. Despite the absence of raw materials suitable for microblade production, the underlying technological adaptations visible at ZL05 during the LGM might be considered equivalent to those at PY03, Shuidonggou, and even Xiachuan where true microblade technology does exist during the LGM.

We echo previous suggestions (Madsen *et al.*, 2001; Brantingham *et al.*, 2004a; Brantingham *et al.*, 2004b) that the composite tool technology of the EUP provided the substrate into which the succeeding fluorescence of microblade technology was easily incorporated. This began initially during the MIS3, but expanded rapidly and significantly following the LGM.

Clearly, microblade technology does not originate as a product of post-glacial adaptations. Furthermore, if northeast Asia was not uniformly abandoned during the LGM then simple recolonization cannot explain the rapid fluorescence of hunting adaptations based on microblade technology. Acceptance of these points warrants alternative explanations for the post-glacial explosion of microblade adaptations.

7. A Speculative Model of Cultural Evolution in Northeast Asia

7.1 The Evolution of Extended Social Networks During the LGM

Northeast Asia was not depopulated during the LGM. However, environmental deterioration did force human foragers into the narrow refugia of a marginal, northern latitude environment. During this time, increasing aridity across northeast Asia and the retreat of temperate grasslands deep into the Loess Plateau and the north China Plain gave rise to demographic packing along the margins of the expanding deserts where more people were aggregated in fewer inhabitable areas. Since most of the landscape was uninhabitable, access to limited resources in circumscribed areas became highly contested, and territorial competition for these limited resources placed additional limits on the long-established practice of managing resource depression with simple mobility. With mobility an insufficient solution to the hazards of resource shortfall, alternative adaptive strategies emerged from the pre-existing tapestry of EUP adaptations already in place across northeast Asia.

Two alternative strategies for managing the hazards of resource shortfall are storage and diet-breadth expansion (see Madsen and Elston this volume). Either or both of these organizational alternatives were likely solutions to the inevitable resource shortfalls resulting from the punctuated cold/dry intervals associated with winter monsoon dominance during the Late Pleistocene of northeast Asia. However, we suggest that the prolonged environmental deterioration of the LGM may have necessitated the evolution of institutional solutions to cope with the frequent hazards of subsistence shortfall.

Institutional, group-beneficial adaptations are abundant in the ethnographic literature of Holocene hunter-gatherers. For the !Kung of southwest Africa and for many Aboriginal hunter-gatherers of central Australia, social institutions answer the ever-present threat of resource depression in arid, marginal environments. The *Hxaro* system of mutual, reciprocal exchange enables the !Kung to average subsistence risk across a network of individuals separated by up to 200 km (Weissner, 1977; Weissner, 1982). Similarly, the elaborate section and subsection marriage systems of Aboriginal Australia establish predefined alliances between biologically unrelated individuals, providing small mobile groups with insurance against the recurrent economic hardships of a spatially and temporally variable environment (Yengoyan, 1968). Both are examples of group-beneficial, institutional solutions to resource depression, and we suggest that similar institutional adaptations emerged during the LGM in northeast Asia.

The evolution of complex, social or institutional solutions to marginal environments during the later Paleolithic is not a new idea. In particular, the Upper Paleolithic expansion of modern humans throughout Europe is seen as a triumph of social rather than technological or biological adaptation (Gamble, 1983; Gamble, 1986). For both Gamble and Whallon (1989), human occupation of extreme environments is contingent upon the existence of integrated social networks capable of transferring information, mates, and resources over great distances. While the ethnographic record bears witness to these propositions, the difficulty is in identifying the conditions under which such extended networks might evolve and then in finding the archeological evidence to confirm it. The truth of the matter is that extended, long-distance social networks do not evolve in an undifferentiated, disarticulated population of individuals spread out over vast tracks of land. Rather extended social networks and the institutions that maintain them likely evolve when individuals combine to form cohesive social groupings and when there are distinct differences between neighboring groups.

7.2 Coordinated Group-beneficial Behavior Evolves Only by Group Level Selection

While adaptive solutions such as technological innovation, mobility, and even diet-breadth expansion may evolve by natural selection acting on individual variation, elaborate social institutions shared by genetically un-related individuals distributed over vast tracks of uninhabited land do not. Instead, the evolution of coordinated group-beneficial behaviors only occurs under a narrow range of conditions where natural selection acts on the adaptive capacity of the entire group. The conditions that provide for group selection have been established with formal, mathematical models couched in the evolutionary dynamics of population genetics (Boyd and Richerson, 1985; Wilson and Sober, 1994; Soltis *et al.*, 1995; Boyd and Richerson, 2002; Richerson and Boyd, 2005). We offer only a basic outline of them here.

On any level, natural selection acts on phenotypic variation. By comparison to organic evolution, cultural evolution generates phenotypic variation rapidly both within and between groups of people. Specifically, significant between-group variation allows selection to act on the level of the group whereas typical Darwinian natural selection acts on the adaptive variation between individuals. Therefore, the emergence and maintenance of between-group variation are essential components of evolution by group selection.

Theoretical modeling suggests that between-group variation will be maintained through punishment (enforcement of the social norms that maintain group-beneficial behaviors) (Hirshleifer and Martinez Coll, 1988; Boyd and Richerson, 1992), conformist social learning (where people learn by imitating the most common behavior) (Henrich and Boyd, 1998), or some combination of the two. Predispositions towards moralistic punishment and conformist social learning are thought to represent the "tribal instincts" of an evolved general psychology, itself a product of long-term environmental variation during the early Pleistocene history of modern humans (Richerson and Boyd, 1998; Richerson and Boyd, 2000; Richerson and Boyd, 2001; Richerson *et al.*, 2003; Richerson *et al.*, 2005). For either of these processes to give rise to group selection, the rate of migration between the groups must be low enough to prevent the erosion of the cultural differences that keep the groups distinct.

In addition to heritable, stable variation between groups, intergroup competition is necessary for behavior to evolve by group selection; that is, there must be a competitive imbalance between groups. Initially, group-beneficial cultural variants (e.g., formal institutions that provide for resource-redistribution or sharing in times of need) are most likely to spread to an entire group when the group is small, and such diffusion is possible through stochastic processes analogous to genetic drift (Richerson and Boyd, 2005). Once established within a single cohesive group, group-beneficial variants can spread to other groups by two distinct processes: differential survival and differential diffusion (Boyd and Richerson, 2002). The former amounts to local extinction when one group outcompetes another leading to either complete dissolution or assimilation of the less competitive group. This slow process of group selection may require as much as 1500 years to produce widespread, group-level adaptations (Soltis *et al*., 1995). Differential diffusion, however, will allow group-level adaptations to evolve and spread much more rapidly. Here, imitation of successful neighbors, also called "prestige-biased transmission" (Henrich and Gil-White, 2001; Henrich, 2001), facilitates the rapid spread of entire packages of cultural behavior between and within spatially structured populations (Boyd and Richerson, 2002). Finally, and critically, if differential diffusion allows group selection to act on group-beneficial behaviors there must be regular interaction between groups with different adaptive strategies. Without this regular interaction, intergroup competition will be weak and natural selection will not act on the level of the group.

7.3 Archeological Signatures of Group-Level Adaptation

Unfortunately, current archeological methodology cannot provide direct, unequivocal evidence for prehistoric social institutions. However, the conditions promoting the evolution of group-beneficial adaptations via group selection do have material correlates and these may be extracted from the archeological record. Archeology must provide evidence for this evolution in the following sequence: (1) the existence of small, independent foraging groups; (2) measurable between-group cultural variation; (3) mechanisms that maintains between-group variation; (4) interaction between groups; (5) competition between groups; and (6) the rapid spread of cultural attributes to reflect the outcome of between-group competition.

Novel adaptive solutions such as group-level cooperation and resource sharing can emerge by chance in small groups of human foragers. The archeological record of Paleolithic hunter-gatherers in northern China suggests that population densities were relatively low throughout the Pleistocene. Paleolithic archeological deposits are stratigraphically thin, typically containing only a few hearths and small clusters of stone tools.

The formal modeling described above requires measurable between-group cultural variation. On a microscale, this variation will be difficult to detect given the low probability of archeological preservation. However, if we accept the dates provided for pre-LGM microblades at Dingcun and Caisi in north China (Lu, 1998), the occasional appearance of such novel technological variants suggests that cultural evolution can and will generate isolated solutions to local adaptive problems. Locally adaptive solutions will produce strong between-group variation when populations are spatially segregated. The emergence of localized, geographically isolated cultural variation is analogous to allopatric speciation in biological populations (e.g., Mayr, 1963: 278–295). Two lines of archeological evidence point to geographic cultural speciation in northern China: spatial aggregation and segregation during cold/dry periods and regional differences in toolstone use and manufacture. A third possible measure of between-group variation is symbolic or "ethnic" marking (McElreath *et al*., 2003). Though common in the Paleolithic record of other parts of the world (Conkey, 1978; White, 1993; Kuhn *et al*., 2001; Close, 2002), with a few notable exceptions symbolic representation is conspicuously absent from the Paleolithic of north China. Therefore between-group differences most likely emerged and solidified through isolation rather than through the evolution of ethnic markers.

For group selection to act on any cultural variant, including cooperative behavior, there must be competition between groups. In this case, "competition" is not limited to direct aggressive conflict between groups, merely that one group must have a competitive advantage over another for survival and reproduction. This competitive advantage must be visible to members of both competing groups and this requires interaction between groups. Group selection is therefore unlikely to act on spatially isolated populations. Rather, the initial selective pressures occur when small, previously isolated groups are forced to compete for limited, localized resources during the cold/dry intervals of MIS3, and particularly during the LGM (Figure 9). With climatic amelioration, human groups once again expand their foraging range, taking with them the group-level behaviors and identities. This expansion brought previously isolated groups into contact, and those groups with well-defined social networks were able to outcompete those groups without. This competitive process led to the rapid spread of behavior, and perhaps technology, as natural selection once again acted on the level of the group. The final archeological testament to this process is the extremely rapid spread of microblade technology across northeast Asia during the post-glacial period.

In broad strokes, the archeological record does meet the necessary conditions for the evolution of group-beneficial behavior by group selection. Additional data and directed research may crystallize the local and regional dimensions of these necessary conditions. At the moment, the most tangible evidence in support of this hypothesis – the rapid and widespread post-glacial appearance of microblade technology – is also the phenomenon we desire to explain.

7.4 Social Networks and the Diffusion of Microblades

We suspect the rapid post-glacial appearance of microblade technology, as evidenced by its "geologically instantaneous" florescence in Siberia (Brantingham *et al*., 2004b, p. 280), resembles the "S-shaped" sigmoid adoption curves identified in the diffusion of innovations literature (e.g., Rogers, 2003, p. 11). The spread of such innovations requires an interconnected population capable of transmitting detailed information between individuals within groups and between groups. While the technological identity of

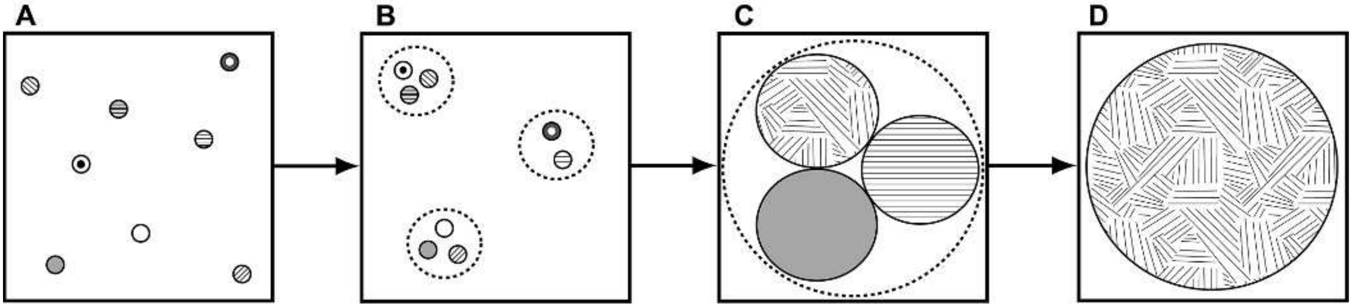

Fig. 9. A schematic of evolution by group selection and the diffusion of innovations. "A" represents small groups of random walk hunter-gatherers dispersed over the landscape during MIS3. We assume that group-functional behavior predominates in at least one of these small groups. In "B" the environmental circumscription of the LGM forces previously independent groups into competition for localized and limited resources. Ultimately, one adaptive strategy outcompetes all others and all individuals in the local area adopt the cultural markers and behaviors of the most successful group. Each group then evolves in isolation (analogous to allopatric speciation). We assume that group-functional behavior helped one of the small groups in the top-left cluster to outcompete all other groups in the cluster. During "C" post-glacial climatic amelioration facilitates expansion into previously uninhabitable landscapes bringing previously independent groups into competition once again. The group in the upper-left possesses an adaptation for group-functional behavior; the others do not. In "D" the group with the group-functional behavior outcompetes its neighbors and the cultural markers and behaviors of this group spread throughout the entire region.

the EUP spread via human migration over tens of thousands of years, the more complex technological knowledge associated with microblade production spread between people, already dispersed over a broad geographic region, in only a few thousand.

During MIS3 the primary locus of human cultural adaptation was local and individual. Adaptations emerged on the strength of local adaptive solutions and spread primarily through migration. The evolution of group-functional behavior was made possible by the range contraction and subsequent concentration of hunter-gatherer groups in narrow refugia across northeast Asia during the LGM. It was demographic packing that brought small, previously independent band-level groups into stable interaction spheres and enabled the evolution of coordinated, group-beneficial behavior. Without this recurrent and prolonged interaction, human groups might never have developed the social coordination necessary for the evolution of well-delineated ethnic memberships, nor would they have had the power to institute and enforce the social sanctions necessary to sustain group-beneficial adaptations.

Post-glacial climatic amelioration alleviated this demographic packing and saw the expansion of symbolically marked, extended social networks into extensive territorial holdings. As each of these extended social networks was exposed to new, perhaps superior adaptive strategies, such as microblade tool technology, these strategies spread rapidly throughout the territorial range of the network via conformist social transmission. When a technological adaptation well suited to the environmental uncertainty of the post-glacial period reached the borders of an initial territorial range of the network, it was picked up by members of the adjacent territory and spread rapidly to the extent of its borders. Local limitations in raw material abundance were answered through trade and exchange between members within the extended and coordinated social network. Access to high-quality raw materials was no longer contingent upon direct access to them.

We suggest that the rapid post-glacial proliferation of microblade-based adaptations across northeast Asia was facilitated by social transmission and not merely by migration or colonization. This rapid "diffusion of innovations" was made possible by the evolution of coordinated, group-functional institutions that emerged by necessity during the environmental deterioration of the LGM.

8. Conclusion

Ultimately, our understanding of the evolutionary trajectory that attends the broad-spectrum revolution and later, the agricultural revolution, hinges on our ability to reconstruct the evolution of group-level coordination and group-functional adaptation rather than the appearance or disappearance of specific and perhaps idiosyncratic artifact types.

Most research on Pleistocene cultural evolution assumes more or less individual actors, independent of group-level behavior. Given the likelihood of extremely low population densities for much of the Paleolithic, this perspective is perhaps reasonable. But when archeological data suggest concentration, demographic packing, or population aggregation, we should take note. During these times, the potential for the evolution of social institutions that fundamentally alter the ways in which human foragers manage their environment and transmit information is staggering.

We suggest that ecological conditions in northeast Asia during the LGM provided the right context for the evolution of long-distance cultural continuity and interaction. The evolution of such group-beneficial behavior between unrelated individuals enabled small corporate groups to withstand the periodic but pronounced resource shortfalls characteristic of marginal environments in northern latitudes. In concert with localized technological evolution, population growth, and climatic amelioration during the post-glacial period, group-beneficial behaviors enabled human foragers to expand rapidly into other, previously inaccessible margins such as the Siberian Arctic, the Tibetan Plateau, Beringia, and ultimately North America. This hypothesis echoes older explanations for the cultural and demographic expansions seen in the Upper Paleolithic record of Europe (Gamble, 1983; Gamble, 1986) and elsewhere (Whallon, 1989). That similar group-level adaptations evolved in other parts of the world at different times does not require cultural continuity with northeast Asia, but merely similar demographic and ecological conditions as those seen in northeast Asia during the LGM.

Finally, since well-demarcated social entities defined inwardly and outwardly on the basis of pottery, architecture, land-use practices, and settlement hierarchies are the hallmarks of Neolithic society, the evolution and persistence of Neolithic social systems during the Holocene is predicated on the existence of highly structured group-level coordination. Without it, agricultural subsistence itself would not be possible. With it, the Neolithic *culture* of agriculture spreads rapidly, at the expense of hunter-gatherers and their group-level adaptations, to all but the most intractable of landscapes.

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A short chronology for the peopling of the Tibetan Plateau

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Abstract

Archeological research over the past several years has started to provide evidence relevant to understanding both the timing of and processes responsible for human colonization of the Tibetan Plateau. This harsh, high-elevation environment is known to exact a heavy demographic toll on recent migrants, and such costs likely erected a substantial biogeographic barrier to initial human colonization. This chapter presents a series of simple metapopulation models that link processes of colonization to mutually exclusive archeological predictions. Current archeological evidence from the northern Tibetan Plateau suggests that seasonal forays into high elevation settings were "adaptive radiations" coincident with the appearance of both Early (ca. 30 ka) and Late Upper Paleolithic (ca. 15 ka) adaptations in low-elevation source areas around the Plateau. More permanent occupation of the Plateau probably did not begin before ca. 8200 ka and may have been driven by "competitive exclusion" of Late Upper Paleolithic foragers from low-elevation environments by emerging settled agricultural groups. The appearance of specialized epi-Paleolithic blade and bladelet technologies on the high Plateau, after 8200 ka, may indicate "directional selection" impacting these new full-time residents. An adaptive radiation of agriculturalists into the mid-elevations of the Plateau, this time leading to year-round occupation, is again seen after 6000 Cal yr BP. The short chronology presented here contradicts genetic-based models suggesting that human populations may have been resident on the Tibetan Plateau for as long as 30,000 years. If the short chronology withstands further empirical scrutiny, it suggests either that initial colonists were genetically predisposed to the rapid accumulation of mutations leading to successful physiological adaptation, or that high-elevation selective pressures are much more severe than usually conceived.

1. The Biogeographic Problem

Few environments are as harsh and unforgiving as the Tibetan Plateau. With an average elevation of approximately 5000 m above sea level (a.s.l.) (Fielding *et al.*, 1994), temperatures on the Tibetan Plateau are uniformly cold, precipitation is sparse, and floral and faunal diversity and abundances are low. Because of low atmospheric pressure at altitude, oxygen is also a rare commodity, a fact that has important and far-reaching consequences. These harsh conditions have well-known negative impacts on human demography. Generally, fertility is much reduced and mortality much increased among recent migrants to high elevation (Moore *et al.*, 2000; Moore *et al.*, 2001; Barker and Hanson, 2004; Moore *et al.*, 2004). While many of these severe demographic costs to life at high elevation have been solved evolutionarily among long-resident populations (Beall, 2001; Beall *et al.*, 2004), there was likely a substantial biogeographic barrier to initial human colonization of the Plateau. Delineating how and when human populations managed to colonize this extreme environment thus may reveal much about the evolution of human biogeographic capacities (Brantingham *et al.*, 2003).

The simplest possible model for the colonization of an environment envisions the recipient area to be colonized as connected to a large, stable metapopulation (MacArthur and Wilson, 1967; Brown and Lomolino, 1998; Hubbell, 2001). The large metapopulation ensures that there is an endless supply of potential colonists, while its stability suggests that colonists of different types exist in fixed (but not necessarily equal) frequencies. Colonists move from the metapopulation into the recipient area according to some dispersal process, usually associated with the reproductive cycle or population growth, and either establish a successful colony, or fail to do so. Successful colonization has a very specific meaning in metapopulation models. It refers to the

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establishment of a population that is continuously present from the moment of colonization (i.e., it is not there only seasonally) and is capable of successfully reproducing over more than one generation, ensuring continuity in genetic and (if relevant) cultural information. Successful colonization does not mean that populations do not fluctuate within the recipient area, just that there is no local extirpation following colonization. Moreover, a population that is established within a recipient area need not be isolated from the metapopulation. On the contrary, the recipient population may receive a continuous stream of dispersers from the metapopulation. Continuous contact with the metapopulation may be particularly important in a suboptimal habitat that inflicts heavy costs in terms of mortality and fertility. Repeated dispersals from the metapopulation might, in this context, "rescue" the recipient population from extirpation. However, repeated rescuing also tends to work against the development of specialized local adaptations by diluting the effects of selection. In the absence of a "rescue effect," one might expect the evolution of adaptations (behavioral and/or biological) to offset the costs of life in a suboptimal habitat. In other words, the colonizing population becomes self-sustaining and does not need rescuing from the meta-population.

2. Plateau Colonization Models and Archeological Predictions

From the general model presented above it is possible to derive a series of specific models for assessing the primary mechanisms driving colonization of the Tibetan Plateau. These simple models are more tractable than a full metapopulation model recognizing that the Tibetan Plateau is a vast region for which we have only limited archeological information. Each of the models is based on the following assumptions about initial conditions. First, assume that the core biogeographic problem lies in how human groups, resident as a metapopulation in the low-elevation source areas surrounding the Plateau, successfully colonized any portion of the high Plateau. We can represent the essential components of this problem abstractly as two areas, one for the low-elevation source area and one for the high-elevation recipient area to be colonized (Fig. 1A). The two areas are assumed to be connected by one or more corridors that would allow colonization of the high-elevation area if the appropriate conditions to drive colonization are present within the source area metapopulation. Initially, the source area is occupied by a population presenting an adaptation *A*, the unique set of behavioral attributes that makes survival in the low-elevation area possible (Brantingham *et al.*, 2004b). However, adaptation *A* is unsuited to colonization of the high-elevation recipient area. In other words, there is a hard biogeographic barrier between the low-elevation source area and the high-elevation recipient area. The obvious archeological prediction based on these initial conditions is that the low-elevation area will contain archeological sites with a unique adaptive signature *A*, but that there will be no contemporaneous archeological record in the high-elevation area.

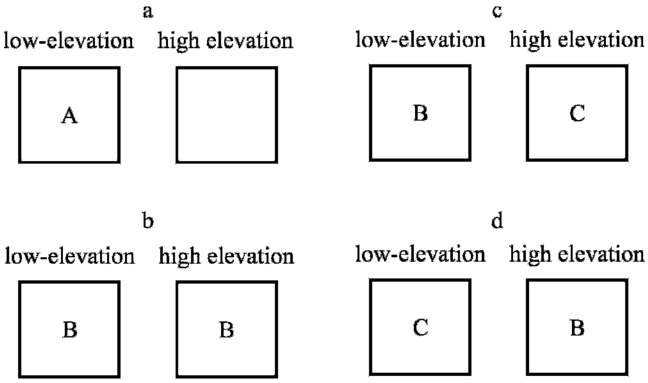

Fig. 1. Metapopulation models for the colonization of the Tibetan Plateau. a, initial conditions have the low-elevation source area occupied by a populations presenting an adaptation A unsuited to colonization of the high-elevation source area. The high-elevation recipient area is unoccupied. b, an adaptive radiation occurs when an adaptation B evolves within the low-elevation source area and is sufficient to allow colonization and survival in the high-elevation environment without any subsequent modifications. c, directional selection occurs if a population moving into the high-elevation environment finds that its low-elevation adaptation is insufficient for long-term survival. Strong selective pressures in the high-elevation environment drive the appearance of new traits C to ensure survival. d, competitive exclusion occurs when some low elevation groups favor retaining ancestral adaptive traits B over adoption of a novel adaptation C and are forced to occupy more marginal habitats as a result.

Model 3: *Adaptive Radiation*. We can extend the model of initial conditions to consider a case where a new adaptation *B* evolves within the low-elevation source area and replaces adaptation *A*. For example, this new adaptation might consist of different mobility strategies, novel forms of social organization, or new technologies that alter the relationship between humans and their resource base. Assume also that adaptation *B*, unlike the ancestral adaptation *A*, is sufficient to ensure colonization of and survival in the high-elevation area. The biogeographic barrier between the source and recipient area collapses and individuals from the low-elevation area colonize the high-elevation area, deploying adaptation *B without modification* (Fig. 1B). We will refer to this process as an "adaptive radiation" (Schluter, 2000). It is critical to recognize that selective pressures present in the low-elevation environment were responsible for driving the emergence of adaptation *B*. In other words, adaptation *B* did not evolve to deal with the biogeographic barrier between areas. Rather, the collapse of the barrier was merely a *byproduct* of evolution in response to some other selective conditions. There are four primary archeological predictions based on this model of adaptive radiation. First, low-elevation sites should show the emergence of novel adaptive traits *B*, replacing ancestral adaptive traits *A*. Second, high-elevation sites should show *exactly* the same adaptive traits *B* seen in low-elevation sites. Third, the high-elevation sites with *B* should be of equal age or younger than sites in low-elevation environment showing *B*. Finally, to be uniquely representative of an adaptive radiation, sites in high-elevation areas *must be older* than any sites in lower elevation areas presenting additional novel adaptations *C* (see below).

Model 2: *Directional Selection*. An alternative model also begins with a new adaptation *B* evolving in the low-elevation source area. Adaptation *B* allows some limited initial expansion into the high-elevation recipient area, but it is insufficient on its own to ensure successful colonization of the high-elevation area. Unique traits evolve in the high-elevation area and the resulting new adaptation *C* is sufficient to ensure survival (Fig. 1C). In this case, we can say that the evolution of adaptation *B* softened the biogeographic barrier between areas, but unique selective pressures in the high-elevation environment were ultimately responsible for ensuring successful colonization. In other words, the observed adaptive traits in the high elevation are not a simple byproduct of evolutionary processes operating in low-elevation environments, but a direct response to the biogeographic problem of colonizing an extreme environment. We refer to this process as “directional selection.” Four archeological predictions arise from this simple model. First, low-elevation sites should show the emergence of novel adaptive traits *B*, replacing ancestral adaptive traits *A*. Second, high-elevation sites should show novel adaptive features *C* not seen in low-elevation sites. Third, the high-elevation sites with *C* should be of equal age or younger than sites with *B* seen in low elevation. Finally, however, the sites with novel features *C* should either be unique to the high-elevation area, or older than any sites with *C* seen in the low-elevation area. This last prediction is necessary to allow for the possibility that specialized adaptations evolved in the extreme, high-elevation area may have been exported subsequently to low-elevation environments.

Model 3: *Competitive Exclusion*. A final model also begins with the emergence of a new adaptation *B* in the low-elevation source area. While this adaptation might have ensured a minimum level of survival within the high-elevation area, little or no occupation actually ensues. At some later point in time, a second novel adaptation *C* appears in the low-elevation area. Segments of the low elevation population retaining – for whatever reason – the ancestral adaptation *B* are displaced or marginalized into high-elevation area, rather than being replaced by *C* (Fig. 1D). In this case, we might say that the evolution of adaptation *B* softened the biogeographic barrier between areas, but that additional demographic or cultural pressures in the low-elevation area ultimately were necessary to drive the dispersal of individuals onto the high Plateau. We refer to this process as “competitive exclusion”. Four archeological predictions may be derived from this model. First, low-elevation sites should show the emergence of novel adaptive traits *B*, replacing ancestral adaptive traits *A*. Second, low-elevation sites should show emergence of a second set of novel adaptive traits *C*, replacing adaptive traits *B*. Third, high-elevation sites will show a retention of the ancestral traits *B* and should be contemporaneous with or younger than sites with *C* seen in the low-elevation area. Finally, sites with features *B* should be confined to the high-elevation area, or are older than any sites with *C* that appear subsequently in the high-elevation area.

These models are clearly simplifications of what must be a complex process. However, they do establish a series of mutually exclusive predictions that may be tested with relatively small data sets. Here we concentrate on evaluating these models with data collected by us and other researchers working in northwest China and the northern Tibetan Plateau (Fig. 2).

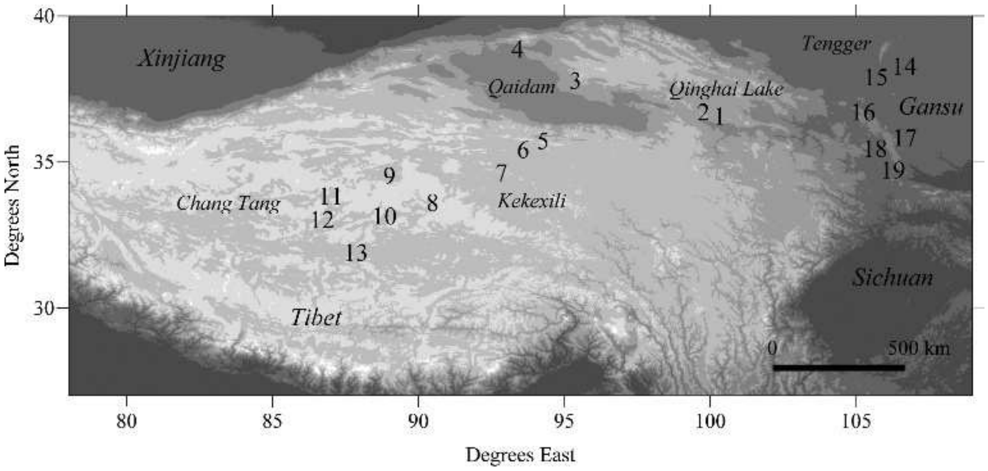

Fig. 2. Digital elevation model of the Tibetan Plateau showing the locations of sites discussed in the text. Middle-elevation step sites: 1, Jiangxigou 1 and 2; 2, Heimahe 1 and 3; 3, Da Qaidam; 4, Lenghu locality 1. High-elevation step sites: 5, Xidatan 2; 6, police station 1 and 2; 7, Erdaogou; 8, Obsidian source at Migriggyangzham co; 9, Dogai coring; 10, Shuanghu; 11, Margog Caka; 12, Yibug Caka; 13, Nyima. Low-elevation step sites: 14, Shuidonggou; 15, Pigeon Mountain; 16, Tongxin; 17, Guyuan (Punyang); 18, Zhuang Lang; 19, Dadiwan Neolithic.

The arid regions of northwest China, including portions of Xinjiang, Gansu, Inner Mongolia, and Ningxia, are treated as the primary low-elevation source area (below 3000 m.a.s.l.) for populations colonizing the northern Tibetan Plateau. The northern Plateau includes all of Qinghai Province and portions of the Tibetan Autonomous Region north of Seling Co (N31.5°). We further subdivide the northern Plateau into two elevational steps; the middle-elevation step (between 3000 and 4000 m.a.s.l.) is represented by the Qinghai Lake basin in the east and the Qaidam Basin in the west. The high-elevation step (above 4000 m.a.s.l.) is bounded in the north by the Muzutag–Kunlun–Anyimaqen Mountain ranges and in the south by the Himalayas. It is topographically undifferentiated (Fielding *et al.*, 1994) consisting of many short river drainages and small, shallow lake basins. Archeological evidence from areas the southern Tibetan Plateau (south of Seling Co) is discussed as appropriate (see also Aldenderfer and Zhang, 2004).

3. Paleoclimate and Paleoenvironment on the Tibetan Plateau

The pattern of Late Pleistocene and Holocene paleoclimatic fluctuations on the Tibetan Plateau and in the surrounding regions is broadly consistent with the global glacial–interglacial sequence (see Wunnemann, this volume). Here we occasionally refer to coarse-grained chrono-stratigraphic makers including Marine Isotope Stage 3 (MIS 3, ca. 50–25 ka[1]), the Last Glacial Maximum (LGM) (ca. 25–15 ka), the post-glacial period (ca. 15–11.5 ka) and the Holocene (<11.5 ka). Primarily, however, we discuss the colonization of the Tibetan Plateau in relation to the Heinrich events (Bond *et al.*, 1992; Bond *et al.*, 1993) as seen in the speleothem $\delta^{18}O$ record from Hulu Cave, Jiangsu Province, China (Fig. 3) (Wang *et al.*, 2001). The Hulu Cave speleothem provides a high-resolution record of the relative strengths of the Southeast Asian Summer Monsoon and the Winter Monsoon (Siberian High Pressure cell) over the last ca. 75 ka (Wang *et al.*, 2001). In general, the cold-dry Winter Monsoon strengthens with increase in $\delta^{18}O$ values in the Hulu record and peaks in intensity during Heinrich events and the Younger Dryas. Conversely, the warm-wet Southeast Asian Summer Monsoon strengthens with decrease in $\delta^{18}O$, with numerous peaks in monsoon strength seen between Heinrich events (Wang *et al.*, 2001). These circulation systems are central to paleoenvironmental fluctuations in continental east Asia. Table 1 lists the calendar ages of Heinrich events H5–H1 and the Younger Dryas, as determined from the Hulu record, as well as two major climatic events of the Holocene determined by other proxies.

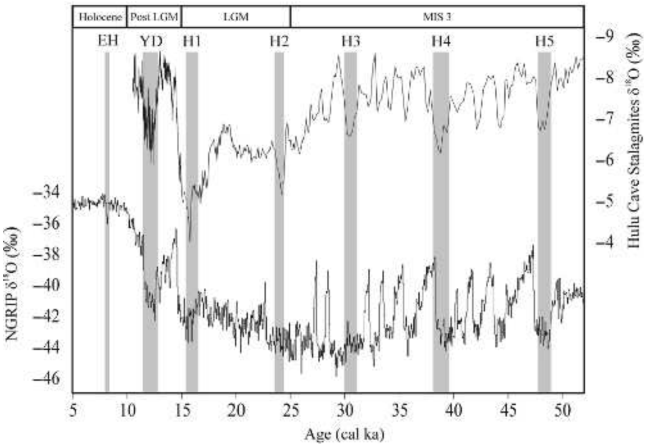

Fig. 3. Hulu and NGRIP oxygen isotope sequence. The Hulu speleothem record is a high-resolution proxy of the relative strengths of the Southeast Asian Summer Monsoon and the winter monsoon (siberian high pressure cell). The NGRIP record is a proxy of global continental ice volume and provides a broad measure of global temperatures. Shown in light gray are the cold-dry heinrich events

Table 1. Ages of Sub-Milankovitch Scale Climatic Events in China.

Event	cal BP	standard deviation
Holocene aridification	4,000	-
Holocene cold-dry event	8,200	-
End Younger Dryas[a]	11,473	80
Start Younger Dryas[a]	12,823	80
H1[b]	15,781	-
H2[b]	24,180	-
H3[b]	30,490	-
H4[b]	38,800	-
H5[b]	47,990	-

[a] Ages estimated from the Hulu records by Wang *et al.* (2001); [b] Age estimated by author from published Hulu record.

Major characteristics of the low-elevation environments bordering the northern Tibetan Plateau are controlled by the balance of precipitation and evaporation and, consequently, on the location of the northern boundary of the Southeast Asian Summer Monsoon (Winkler *et al.*, 1993). As this boundary has fluctuated over the course of the Late Pleistocene so has the location of desert-Loess Plateau transition, the sizes of internally draining lakes and the distribution of flora and fauna. In general, northwest Chinese deserts were at least as large as at present during the Early Glacial, before H5 (ca. 47.9 ka) and again between H2 and H1 (24.2–15.8 ka) (Xiao *et al.*, 1995; Ding *et al.*, 1999; Bush *et al.*, 2002). They were substantially smaller than present during the Early Holocene (11.5–8.2 ka) and during portions of MIS 3. Lake high stands are correlated with the warm-wet events that followed H4 (ca. 38.8 ka) and H3 (ca. 30.5 ka) (Fang, 1991; Pachur and Wünnemann, 1995; Zhang *et al.*, 2004) (Wunnemann, this volume). Most basins were

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[1] All ages reported in thousands of years before present (ka) are calibrated unless otherwise indicated.

completely dry between H2 and H1 (ca. 24.2–15.8 ka), and much smaller lakes appeared again in only during the Holocene. Steppe grasslands may have been at their largest extents, and maximum taxonomic diversity, in the periods immediately following H4 (38.8 ka), H3 (30.5 ka) and H1 (15.8 ka) (Herzschuh, this volume). They were greatly reduced in size and diversity between H2 (24.2 ka) and H1 and probably also during earlier Heinrich events. There is general recognition that conditions were warm and wet during the Early Holocene, but there appears to some regional variability in this pattern. The deserts of northwest China may have been persistently more arid from the Younger Dryas on. The western Loess Plateau, by contrast, seems to have supported *Betulus*, *Querqus* and *Ulmus* forests during the Early Holocene (Chen *et al.*, 2003; An *et al.*, 2004). Both areas register a brief period of cold-dry conditions around 8200 Cal yr BP, which appears to be a Heinrich-like event (Wang *et al.*, 2002a; Clarke *et al.*, 2003; Morrill and Jacobsen, 2005; Schmidt and LeGrande, 2005). Both north and northwest China become increasingly arid following ca. 7800 Cal yr BP and there is a precipitous drop in humidity ca. 4000 Cal yr BP (An *et al.*, 2005). Faunal communities, including many of the medium and large-sized ungulates present today on the Tibetan Plateau (Schaller, 1998), may have readily tracked these fluctuations by altering their geographic distributions. However, there is a lack of evidence to say much more than this.

Climatic and environmental conditions on the middle-elevation step of the northern Plateau parallel those in the surrounding low-elevation areas. In particular, many of the large, internally draining lake basins appear to have reached maximum high stands during MIS 3, roughly 35-25 ka (Chen and Bowler, 1986; Huang *et al.*, 1987; Ma, 1996; Owen *et al.*, 2006). All of the lakes on the middle-elevation step appear to have been dry between H2 (ca. 24.2 ka) and the Early Holocene (<11.5 ka), when shallow, saline lakes reemerged in some basins. Vegetation histories, though poorly known, suggest that coniferous forests (primarily *Picea*, *Pinus*, and *Abies*) occupied the slopes of the Qilian Mountians during the middle portion of MIS 3, with steppe or desert steppe dominating the basin bottoms (Herzschuh, this volume). Desert steppe remained widespread following the LGM and was replaced with alpline steppe and meadow in some areas (e.g., Qinghai Lake basin) only with the return of greater humidity during the Early Holocene (Herzschuh, this volume; Wunnemann, this volume).

Despite forceful claims to the contrary (e.g., Kuhle, 1999), at no point during the Late Pleistocene does there appear to have been a continent-sized ice sheet covering the Tibetan Plateau (Benn and Owen, 1998; Owen *et al.*, 2003). Rather, discrete periods of glacial advance were restricted primarily to montane valleys. Glaciation on the high Plateau as a whole is controlled by the availability of moisture, since temperatures are always low enough to ensure ice buildup. However, the timing of ice buildup along the southern boundary of the Plateau is asynchronous with that along the southern boundary; the Himalayas receive most of their precipitation from the South Asian Summer Monsoon, which strengthens during interstadials and interglacials, while the Kunlun–Muzutag–Anyimaqen receives most of its moisture from the Westerly Jet Stream, which strengthens during stadials and glacials (Benn and Owen, 1998; Owen *et al.*, 2005). Lake systems on the high Plateau are complex, reflecting hydrological contributions both from low and high-pressure circulation systems as well as glacial ice melt. In general, moderately large lakes may have been present on the high step of the Plateau before H2 (ca. 24.2 ka) (Wang *et al.*, 2002b). These were greatly reduced in size during the LGM and, following glacial termination (ca. <15.8 Cal yr BP), expanded to reach their highest stands of the Late Pleistocene, fed by abundant glacial meltwater (Wei and Gasse, 1999). Most lakes for which we have a record show progressive desiccation over the course of the Holocene. We know much less about Late Pleistocene and Holocene floral and faunal communities on the high-elevation step of the Plateau. Holocene pollen records from lakes on the western (e.g., Sumxi Co) and eastern (e.g., Zoige basin) extremities of the high Plateau suggest that floral communities alternated between steppe and desert-steppe during warm-wet and cold-dry events, respectively (Vancampo and Gasse, 1993; Yan *et al.*, 1999). On the northern high Plateau, where conditions are far more arid today, the alternation may have been between desert-steppe and unvegetated landscapes. Fauna must have tracked these changes – populations growing in size and expanding their range under steppe conditions, but suffering severe reductions in size and range contractions under desert-steppe or desert conditions (Schaller, 1998).

4. The Chronology of Human Colonization

The Low-elevation Source Area. The number of dated archeological sites in low-elevation environments surrounding the Tibetan Plateau has grown apace in recent years. Irrespective of their archeological characteristics, these sites provide compelling evidence that at least some portion of the low-elevation source area of the Plateau was continuously occupied from 35 ka onwards, though population sizes and distributions may have fluctuated widely in response to climatic and environmental change. Numerous sites in northwest China are now confidently dated to MIS 3, with the largest cluster of sites falling in the time period immediately preceding and during H3 (ca. 30.5 ka) (see Barton, Brantingham, and Ji, this volume). The best known of these sites is Shuidonggou, located on the western margins of the Ordos desert, with dates ranging continuously from ca. 35–29 ka (Madsen *et al.*, 2001; Brantingham *et al.*, 2001a; Ningxia Institute of Archaeology, 2003). Far fewer sites are assigned to the time period between H3 and H2 (ca. 24.2 ka), but several of those that have been identified are in western Gansu (Barton, Brantingham, and Ji, this volume). Shuidonggou Locality 2 contains occupations falling within the earlier part of this period and Tongxin 3, Tongxin 8, and Guyuan 3 fall midway between these events (see also Gao *et al.*, 2004). Farther to the east, the Xiachuan Localities 1 and 2 may have occupations representing the period just prior to the LGM (Barton, Brantingham, and Ji, this volume) (Chen and Wang, 1989; Chung, 2000).

There are nearly as many sites falling, between H2 and H1 (24.2–15.8 ka) – the LGM – as in the preceding time period. Sites reported by Barton, Brantingham, and Ji (this volume) cluster in two events immediately following H2 and immediately preceding H1 (see also Ji *et al*., 2005). Zhuang Lang 5, located on the western Loess Plateau has two archeological horizons dated to ca. 20,070 ± 360 and 24,140 ± 240 Cal yr BP, respectively. A number of well-known sites date to the period following glacial termination. Xiaonanhai and Hutouliang contain stratigraphic components that date to the Bølling–Allerød and the Younger Dryas events (ca. 12.8–11.4 ka) (Lu, 1999). However, these sites lie much to the east of the Tibetan Plateau. The Pigeon Mountain localities, by contrast, are located within the desert source area of the Plateau and are well dated to between 15,135 ± 338 (Beta 97242) and 11,608 ± 183 (Beta 86732) (Elston *et al*., 1997; Madsen *et al*., 1998).

Following the Younger Dryas (ca. 11,473 Cal yr BP) there is a substantial gap in the record of dated sites in the low-elevation source area of the Plateau, which probably reflects a lack of research on deposits of the right age (Madsen and Gao, this volume). By ca. 7800 Cal yr BP we have good evidence for the presence of sedentary agriculture populations on the western Loess Plateau (Lu, 1999; An *et al*., 2004). Occupations remain fairly intense through the Dadiwan (ca. 7800–7350 Cal yr BP), Yangshao (6800–4900 Cal yr BP) and Majiayao Culture periods (ca. 5300–4300 Cal yr BP), but appear to be smaller and more dispersed by the middle of the Qijia Culture period (ca. 4300–3900 Cal yr BP) (An *et al*., 2005).

The Middle- and High-Elevation Steps. Only two archeological sites on the middle-elevation step and a handful of sites on the high-elevation step of the Tibetan Plateau may represent initial human forays onto the Plateau prior to H2 (ca. 24.2 ka). Lenghu locality 1 (N38.85, E93.41, 2,804 m.a.s.l.) is a surface scatter of stone tools found horizontally stratified between two well-preserved beach ridges (Fig. 4). The archeological materials are found above the 45 m beach ridge containing ice wedge casts dated by OSL to 14.9 ± 1.5 ka (Owen *et al*., 2006) and TL to 18.51 ± 2.22 ka (Ma, 1996) (Table 2). The beach ridge preserving the ice wedge casts must correspond to a lake high stand older than H2 (ca. 24.2 ka). The archeological materials are also below the elevation of two higher beaches, one of which may be assigned an age of ca. 37.21 ± 1.13 ka based on radiocarbon dating of carbonate from a lake marl in the same section (Ma, 1996). One of the two higher beach ridges (at 57 or 70 m above the current lake surface) may correlate with the warm-wet event following H4 (ca. 38.8 ka), while the 45 m beach may correlate with the warm-wet event following H3 (ca. 30.5 ka). Given that stone tool assemblages have yet to be found in the Lenghu basin below the elevation of the H3 beach (unpublished field observations), we tentatively assigns these materials a minimum age of around 30.5 ka and maximum age of 38.8 ka. In support of this conclusion, we note that the degree of wind ablation seen on the artifacts is consistent with a very long period of surface exposure. The lithic technologies – Early Upper Paleolithic-type large blade cores and tools (Brantingham *et al*., 2001a) – are consistent with those seen in lower elevation areas surrounding the Plateau at the same time (see below).

The site of Xiao Qaidam (N37.46, E95.52, 3,100 m.a.s.l.) is similar to Lenghu locality 1 in several respects. Stone cores and flakes are found on the surface of a feature interpreted as a relict beach ridge associated with a high stand of

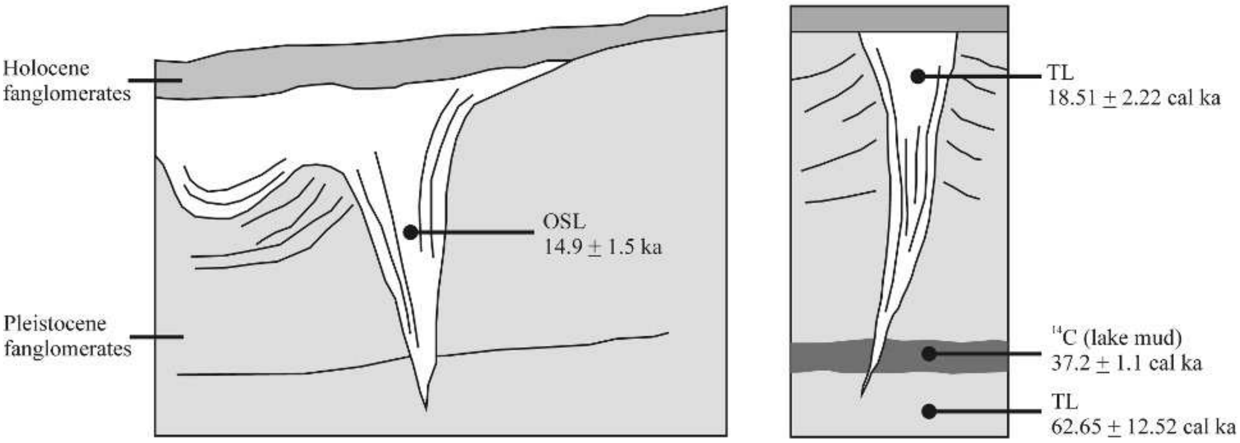

Fig. 4. OSL, TL and radiocarbon dates for ice-wedge casts and other sedimentary features in the ∼45 m beach (ca. 2,780 m.a.s.l.) at Lenghu. The OSL and TL dates on the two separate ice wedge casts indicate that the underlying beach gravels must have accumulated before H1 (15.8 Ka) and probably before H2 (24.2 Ka). The most likely timing for the ∼45 m high stand is the warm-wet event following H3 (30.5 Ka). The radiocarbon dated lake mud in this section may correspond to a lake high stand that formed one of two beaches at ∼57 and ∼70 m above the current lake surface, respectively. Artifacts found on the surface above the ∼45 m and below the ∼57 m beach are assigned a minimum age of ca. 28–30 ka and maximum age of ca. 37 ka based on their horizontal stratigraphic position.

Table 2. OSL and TL Dates.

Site	Unit/Feature/Depth	N	E	Age Cal yr BP	SD	Lab Number	Reference
Heimahe 1	49 cm below surface	36.73	99.77	6,995	520	UIC1568	this paper
Heimahe 1	89 cm below surface	36.73	99.77	15,310	1,080	UIC1570	this paper
Heimahe 1	134 cm below surface	36.73	99.77	11,785	880	UIC1567	this paper
Heimahe 1	159 cm below surface	36.73	99.77	14,940	1,115	UIC1566	this paper
Heimahe 1	234 cm below surface	36.73	99.77	26,550	1,770	UIC1569	this paper
Yeniugou Valley	183 cm below surface	35.92	94.67	8,600	700	QD4A	Owen *et al.*, 2006
Lenghu Ice Wedge Cast	45 m beach	38.85	93.42	14,900	1,500	QBOSL6A	Owen *et al.*, 2006
Lenghu Ice Wedge Cast[a]	45 m beach	38.85	93.41	18,510	2,220		Ma 1996

[a] Thermoluminescence (TL) age

the lake in the Xiao Qaidam basin. Huang (1987) correlates the inferred high lake stand with radiocarbon dated ostracods in a sediment core from the adjacent Da Qaidam basin and assigns a tentative minimum age of 37.9 ± 3 ka to the Xiao Qaidam assemblage based on this correlation. Owen *et al.* (in press) have collected samples for OSL dating of the Xiao Qaidam beach ridge, which might provide better age control for the site. Results of this study are still pending. Our own field investigations at Xiao Qaidam succeeded in relocated Huang's (1987) sites, but failed to find any material associated with the surface lithics that might be directly dated. Of greater concern, however, is our discovery of lithic technologies identical in character to those at Xiao Qaidam (e.g., raw material type, size and shape, technological forms) in direct association with Han Dynasty aged (ca. 2000 Cal yr BP) ceramics in the nearby Iqe River (Yucha He) drainage (unpublished data). This association brings into question the pre-H2 age assignment for the Xiao Qaidam materials.

Several sites have been discussed as representing possible pre-H2 occupation of the high-elevation step of the northern Plateau (An, 1982; Huang, 1994; Brantingham *et al.*, 2001b; Aldenderfer and Zhang, 2004). However, none of these sites have directly associated chronometric dates (see Huang, 1994; Aldenderfer and Zhang, 2004). Age assignments for most of these sites have been based on lithic technological typological systematics, usually emphasizing the presence of Middle Paleolithic-type tools (e.g., side scrapers). Some sites in the Chang Tang, identified by Schaller (1998) and reported by Brantingham, Olsen *et al.* (2001b), have technological characteristics reminiscent of Middle Paleolithic Levallois technology, which might suggest an age of ca. 30 ka, or even earlier (see Brantingham *et al.*, 2001a). But, other assemblages present characteristics that appear to be derived from the northeast Asian Early Upper Paleolithic, which lead Brantingham, Olsen *et al.* (2001b) to suggest that they may be LGM in age, i.e., falling between H2 at 24.2 ka and H1 at 15.8 ka. However, current evidence, discussed in detail below, suggests that these early age assignments may not be warranted. Rather, the lithic technologies seen at sites in the Kekexili, Chang Tang, and other areas of the high Plateau are now reliably dated at one site to the Early Holocene (ca. 8200–6400 Cal yr BP).

Only one site on the entire Plateau has been discussed as falling between H2 and H1. Located approximately 85 km outside of Lhasa, at 4200 m.a.s.l., Chusang (or Quesang) consists of a series of hand and footprints and a possible hearth found in a now-hardened spring travertine (Zhang and Li, 2002; Aldenderfer and Zhang, 2004). Zhang and Li (Zhang and Li, 2002) failed to recover datable charcoal from the possible hearth, but did retrieve what are described as aeolian quartz grains from within the travertine matrix. OSL dates of 20.6 ± 2.9, 21.1 ± 2.1, and 21.7 ± 2.2 ka were determined from these materials, providing possible maximum ages for the hand and footprints. Taken at face value, these ages suggest that human populations may have ventured into high elevations as early as 21 ka. More recent age determinations may suggest an age of around 11 ka (see Aldenderfer, this volume). However, extensive replication of any dates from this site is necessary given the possibility that non-aeolian, detrital sand grains may make up a fraction of the quartz being used for dating. It is unclear whether the Chusang travertine is a carbonate-cemented sediment or a true calcite flowstone. If the former, then any detrital sand grains incorporated from in situ sediment are more likely to be unbleached, leading to OSL ages that are too old.

Three sites in the Qingahai Lake basin register human occupation of the middle-elevation step of the Plateau in the interval between H1 (ca. 15.8 ka) and the beginning of the Younger Dryas (ca. 12.4 ka) (Madsen *et al.*, 2006). Jiangxigou 1 (N36.59, E100.3, 3,330 m.a.s.l.) is a buried archeological site located at the head of a small stream flowing north into Qinghai Lake. The site lies approximately 136 m above the current lake surface. Multiple simple hearth features and associated stone technology, fragmentary bone and large rocks are found buried within an aeolian sedimentary stack. Charcoal recovered from hearth features 1 and 3 yielded AMS radiocarbon dates of 14,690 ± 150 and 14,760 ± 150 Cal yr BP, respectively (Table 3) (Madsen *et al.*, 2006). Similar ages have been obtained from a nearby site, locality 93–13, first identified and dated in 1993 as part of a geomorphological investigation of Qinghai Lake depositional environments (Porter *et al.*, 2001; Madsen *et al.*, 2006). This site also consists of two stratigraphically separate, isolated hearths dating to 14.6 ± .35 and 14.5 ± .33 ka, respectively (Table 3).

Table 3. Radiocarbon Dates.

Site	Unit/Feature	N	E	^{14}C yr BP	^{14}C yr SD	Cal yr BP	Cal yr SD	Sample Material	Lab Number	Reference
Lenghu	highest stand mud	38.85	93.41	31,700	800	37,210	1,130	carbonate	-	Ma (1996)
Jiangxigou 1	Feature 3	36.59	100.3	12,470	60	14,760	150	charcoal	Beta 208338	this paper
Jiangxigou 1	Feature 1	36.59	100.3	12,420	50	14,690	150	charcoal	Beta 149997	this paper
Locality 93-13	Lower hearth	-	-	12,420	120	14,601	348	charcoal	AA-12318	Porter *et al*. (2001)
Locality 93-13	Upper hearth	-	-	12,370	90	14,528	333	charcoal	AA-12319	Porter *et al*. (2001)
Heimahe 1	Surface 2[a]	36.73	99.77	11,480	60	13,390	90	charcoal	Beta 194545	this paper
Heimahe 1	Surface 1	36.73	99.77	11,220	50	13,140	60	charcoal	Beta 194544	this paper
Heimahe 1	Secondary hearth	36.73	99.77	11,160	50	13,080	90	charcoal	Beta 169901	this paper
Heimahe 1	Secondary hearth	36.73	99.77	11,140	50	13,040	60	charcoal	Beta 169902	this paper
Heimahe 1	Primary hearth	36.73	99.77	11,070	40	12,970	60	charcoal	Beta 149998	this paper
Heimahe 1	Loess block	36.73	99.77	11,040	70	12,940	90	charcoal	Beta 194543	this paper
Heimahe 1	Surface 4	36.73	99.77	10,850	40	12,790	50	charcoal	Beta 169903	this paper
Heimahe 1	Surface 4	36.73	99.77	10,670	60	12,690	40	charcoal	Beta 194542	this paper
Jiangxigou 2	max 100 cm depth	36.59	100.3	8,170	50	9,140	90	charcoal	Beta 194541	this paper
Jiangxigou 2	81 cm depth	36.59	100.3	7,330	50	8,130	70	charcoal	Beta 208336	this paper
Jiangxigou 2	60–70 cm depth	36.59	100.3	4,850	40	5,580	60	charcoal	Beta 209350	this paper
Heimahe 3	Primary hearth	36.72	99.78	7,630	50	8,450	50	charcoal	Beta 208334	this paper
Xidatan2	T5 possible hearth	35.71	94.26	5,670	40	6,460	40	charcoal	Beta 194553	this paper

[a] no archaeological remains were found in association with surfaces 1,2 and 4 at Heimahe 1. These may represent natural fires

Heimahe 1 (N36.73, E99.77, 3,210 m.a.s.l.), 65 km to the west of Jiangxigou 1, is situated away from the mountain front in the flood plain of the small Heimahe (he = river). The site lies approximately 16 m above the current lake surface. Two hearth features with associated cultural debris are found buried within a sedimentary stack that grades upwards from fine-grained alluvial deposits to aeolian silts (Fig. 5). The primary hearth has yielded date of 12,970 ± 60 Cal yr BP and a directly associated secondary hearth feature two dates of 13,040 ± 60 and 13,080 ± 90 Cal yr BP. These point to an average age of occupation of 13,010 ± 109 Cal yr BP. Several other burned surfaces have been identified at elevations slightly above and below the hearth features (surface 3), but laterally distributed over a distance of ca. 5 m to the north and south. It is uncertain whether these burn features are cultural in origin. They are broadly consistent in age with the two true hearths identified at the site (Table 3). Close inspection of Fig. 5 and Tables 2 and 3 reveals that the OSL and radiocarbon dates are offset with respect to one another. A complex depositional history for the sediments used in OSL dating, may partially explain the lack of comparability across dating techniques. Overall, the Heimahe 1 sequence appears to have accumulated rapidly ca. 13 ka and that human occupation was approximately coincident with the initiation of sedimentation at the site (Table 2).

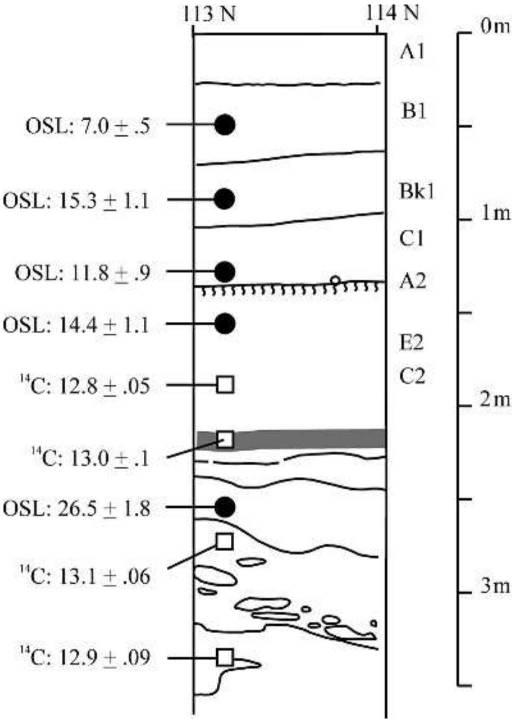

Fig. 5. Schematic stratigraphic section for Heimahe 1 showing the depth of dating samples and the cultural surface. The cultural surface (gray) is found at a maximum depth of about 2.11 m below the surface. The sequence begins as coarse sand alluvium at the base and fines upwards towards silt-dominated alluvium at the top. A pre-Younger Dryas soil is located at a depth of ca. 1.4 m below the surface. OSL dates are shown as filled circle, radiocarbon dates as open squares.

No sites are known presently from the high-elevation step of the Plateau dating to the interval between H1 and the onset of the Younger Dryas, despite having deposits of appropriate age (Brantingham *et al.*, in prep; Van Der Woerd *et al.*, 2002), and neither area has yet to yield sites falling within the Younger Dryas (ca. 12,823–11,473 Cal yr BP). Van Der Woerd *et al.* (2002), however, identified what appears to be a fire hearth on the first terrace (T1′) of the Xiadawu River (N35.0, E99.18, 4,000 m.a.s.l.) located at an unconformity between terrace gravel fill and a ~1-m thick loess deposit. The feature returned a radiocarbon age of 11,010 ± 27 Cal yr BP suggesting a possible human occupation on the high-elevation step of the Plateau shortly after the end of the Younger Dryas. However, this site has not been described by archeologists, so little more can be said about the nature of this possible occupation. Chusang, mentioned above, may also date to ca. 11 ka, though we reiterate our concerns about the geochronology at this site.

An occupation signature is again detected on the middle-elevation step of the Plateau during the Early Holocene, up to and including the Holocene ca. 8200 Cal yr BP cold-dry event. In the Qinghai Lake basin, two sites have been dated to this interval. Jiangxigou 2 (N36.59, E100.3, 3,330 m.a.s.l.), across the drainage from locality 1, is a 1.2-m thick midden and ash deposit with abundant cultural materials. Radiocarbon ages of 9140, 8130, and 5580 Cal yr BP, all in stratigraphic order, suggest that this is a multicomponent site (Table 3). Preliminary OSL dates on small ceramic sherds from the same sequence yielded ages of 6.8 ± .6, 4.4 ± .5, and 1.8 ± .3 ka. These are also in stratigraphic order and consistent with the radiocarbon determinations. They further support the conclusion that this is a multicomponent site. Heimahe 3 (N36.72, E99.78, 3,202 m.a.s.l.), radiocarbon dated to ca. 8450 Cal yr BP, is contemporaneous with Jiangxigou 2. Like the earlier occupation at Heimahe 1, however, Heimahe 3 is an isolated hearth with a small collection of associated cultural debris. The feature is located at a depth of 1.94 m at a transition between alluvial and loess sedimentation.

The oldest, reliably dated site on the high-elevation step of the Plateau is assigned to Early Holocene. Xidatan 2 (N35.71, E94.26, 4,300 m.a.s.l.) lies on the middle (T4) of three glacial outwash terraces in a small unnamed tributary of the Kunlun River (Fig. 6) (Brantingham *et al.*, in prep). Loess overlies the outwash debris on the two upper terraces and varies in thickness from <.3 to 2.0 m. It is eroded in irregular patches leaving blowout depressions between intact loess stacks. Stone cores, flakes, and tools are found at the surface in the blowout depressions over nearly the entire length of the terrace (ca. 385 m), but dense concentrations of artifacts occur midway up the terrace. Small-scale test excavations established that the eroded surface materials originate from a buried context within the loess cap on T4, at an average depth of 30 cm below the surface and 15 cm above the terrace gravels. The age of the Xidatan

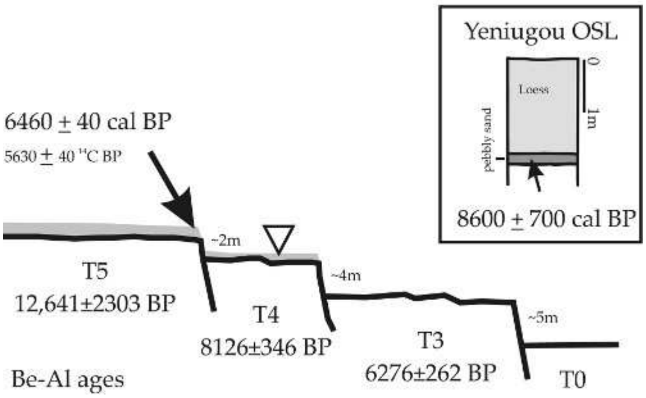

Fig. 6. Be–Al cosmogenic surface exposure, radiocarbon, and OSL ages from the xidatan 2 site and the adjacent yeniugou valley. Be–Al ages determined from terrace gravels by Van Der Woerd et al. *(2002). The OSL date is from a pebbly sand unit underlying a loess cap in the yeniugou valley was determined by Owen* et al. *(in press). The age of the archeological site on T4 (open triangle) is constrained to be younger than ca. 8200 cal yr BP and older than ca. 6400 cal yr BP with a probable age assuming constant loess sedimentation rate of ca. 7800 Cal yr BP (redrawn following Van Der Woerd et al., 2002 and Owen et al., 2006).*

2 lithic assemblage is constrained by cosmogenic surface exposure (CSE) dates (Van Der Woerd *et al*., 2002), one OSL date (Owen *et al*., 2006) and one AMS radiocarbon date (Brantingham *et al*., in prep). Be–Al CSE ages for each of the three terraces at Xidatan 2 were determined as part of a geological study of slip rates along the Kunlun Fault, which runs through part of the site (Table 4) (Gosse and Phillips; Van Der Woerd *et al*., 2002). T5, the highest terrace, yielded a Be–Al age of 12614 ± 2303 Cal yr BP. T4, which holds the Xidatan 2 site, yielded an age of 8126 ± 346 Cal yr BP. The lowest terrace, T3, returned an age of 6276 ± 262 Cal yr BP. These ages date the transition between periods of fan aggradation and periods of renewed terrace down cutting. They also provide limiting ages for the Xidatan 2 archeological site. The materials on T4 can be no older than ca. 8.1 ka. The absence of materials on T5 suggests that there was no occupation at the site between 12.6 and 8.1 ka, while the absence of materials on T3 also suggests that the site on T4 is older than ca. 6.3 ka. Owen *et al*. (in press) report an OSL date of 8.6 ± .6 ka on pond sediments immediately underlying a surface loess cap the adjacent Yeniugou valley (see Table 2). This provides confirmation for the maximum age of the loess at Xidatan 2. We identified a possible hearth feature 16 cm below the surface on T5, 100 m up stream from the main concentration of artifacts on T4. An AMS radiocarbon date of 6460 ± 40 Cal yr BP provides a minimum age for the loess deposits on T4 and T5 as well as the archeological site on T4 (Table 3). Assuming a constant rate of deposition between the onset of loess sedimentation around 8.1 ka and termination around 6.5 ka, the buried materials on T4 date to ca. 7800 Cal yr BP.

We correlate other sites known on the high Plateau with Xidatan 2 on the basis of shared stone raw material types, including a compositionally unique obsidian, and the techno-typological characteristics of the assemblages (see below). We hypothesize that the surface sites from the Chang Tang, previously described by Brantingham, Olsen *et al*. (2001b) as LGM in age, are in fact no older than Xidatan 2. Similarly, a number of other sites in the high elevation Kekexili Reserve (e.g., Police Station 1 and 2, Erdaogou 1) and several on the middle-elevation step (e.g. Da Qaidam and Sogo Nur) are also assigned to the Early Holocene based on the same criteria. None of these sites have independent age determinations, however.

Finally, we note that the first evidence for nonforaging adaptations on the middle-elevation step of the northern Plateau probably postdates 6000 Cal yr BP. The site of Jiangxigou 2 (N36.59, E100.33310 m.a.s.l.) has yielded thick, undecorated and thin cord marked ceramics, as well as abundant fragmentary faunal remains, from a stratified section with radiocarbon dates ranging between 9140–5580 Cal yr BP (Table 3). The oldest of three OSL dated ceramic sherds, at 6.8 ± .6 ka, suggests that ceramic technologies appear in the middle part of the sequence. If these date withstands further scrutiny, then the Neolithic component at Jiangxigou 2 may be as old as, or older than the well-known Neolithic site of Karou, located near Qamdo (N31.09, E97.10,3307 m), nearly 700 km to the southwest (CPAM, 1985; Aldenderfer and Zhang, 2004). The earliest occupations at Karou date to ca. 5758 ± 109 Cal yr BP.

5. Archeological Characteristics of the Metapopulation

The Late Pleistocene archeological sequence in the low-elevation areas surrounding the northern Tibet Plateau is reasonably well known, especially following H4 (ca. 38.8 ka). The Early Upper Paleolithic is first recognized in

Table 4. Be–Al Cosmogenic Surface Exposure Ages.

Site	Terrace Number	N	E	Be-Al mean age Cal yr BP	Cal yr SD	Reference
Xidatan 2	T3	35.71	94.26	6,276	262	Van Der Woerd *et al*. (2002)
Xidatan 2	T4	35.71	94.26	8,126	346	Van Der Woerd *et al*. (2002)
Xidatan 2	T5	35.71	94.26	12,614	2,303	Van Der Woerd *et al*. (2002)

northwest China 34.8–28.7 ka and may be linked to populations moving south from Siberia through Mongolia beginning 45 ka (Brantingham *et al.*, 2001a). At Shuidonggou Locality 1, flat-faced cores, technologically equivalent to a Levallois core reduction strategy, were used to produce large, flat blades that were subsequently retouched along one or both edges (Ningxia Institute of Archaeology, 2003). Stone raw material usage at Shuidonggou appears to be focused on moderate-quality materials that were readily available in alluvial deposits at the site. Retouched tools are generic in character, dominated by types that are considered diagnostic of the Middle Paleolithic including many side scrapers, denticulates, and notches. The later part of the sequence at Shuidonggou Locality 2 may show a trend towards reduction in the sizes of cores and tools, including a turn to bipolar reduction of small chert and quartz pebbles (Madsen *et al.*, 2001). Numerous other sites within reach of the low-elevation areas surrounding the Plateau are coeval with Shuidonggou (e.g., Guyuan 3, Tongxin 3 and Tongxin 8 at 29–30 ka) (Barton, Brantingham, and Ji, this volume; Bettinger *et al.*, this volume) (Ji *et al.*, 2005). These show a similar focus on moderate-quality raw materials and broadly Middle Paleolithic retouched tool types. Levallois-like flat-faced blade technologies too may have featured at these sites (Gao *et al.*, 2004).

Between H2 and H1, 24.2–15.8 ka, Levallois-like large blade technologies disappear and we see a shift towards expedient lithic technologies and the (possibly selective) use of poor quality raw materials. Zhuang Lang 5, dated between 24 and 19.7 ka, for example, appears to represent small scale, occupation centered on bipolar reduction of quartz and fine grained quartzite cobbles (Barton, Brantingham, and Ji, this volume; Brantingham *et al.*, 2004c). We have suggested elsewhere (Madsen *et al.*, 2001) that bipolar reduction yields large quantities of small, sharp debitage that can be easily picked through to find suitable small blanks for use in inset tools, much like formal microblade insets, but without all of the associated stone procurement and production costs (Elston and Brantingham, 2003).

Following H1, at 15.8 ka, we see the intensification of foraging strategies throughout northeast Asia, although there is considerable variability in the local character of archeological assemblages. Intensification is signaled most clearly by the appearance of formal microblade technologies based on pebble, flake and, very occasionally, biface blanks. Evidence from Siberia suggests that these core technologies were used to produce microblades that would be segmented and used as insets in composite point armatures. There is no conclusive evidence for the use of composite points in north or northwest China beyond the prevalence of microblades at most sites of this age, however. It is also unclear exactly when microblades first appear in the Chinese sequence. The site of Xiachuan is often cited as providing the earliest evidence (ca. 19–25 ka) for both the use of microblades and ground stone (Chen and Wang, 1989; Lu, 1999; Chung, 2000). Yet, there is some uncertainty about the association between specific archeological finds and radiocarbon dates across the many Xiachuan localities. The "smash-and-bash" bipolar technology seen at Shuidonggou Locality 2 (Madsen *et al.*, 2001) and Zhuanglang 5 may be an appropriate precursor to a formal microblade technology, suggesting an origin around the end of H1 (15.8 ka) (Barton, Brantingham, and Ji, this volume; Bettinger *et al.*, this volume). But it may also be the case that formal microblade technology did not become an important part of the Late Pleistocene foraging adaptations until the Younger Dryas ca. 12.8–11.5 ka, or shortly before (Elston and Brantingham, 2003). The Pigeon Mountain localities, for example, suggest that the period following H1, ca. 15.8 ka, in the desert margins of the Plateau, is characterized by heavy-duty macrolithic tools as well as simple unifacial and bifacial points (Elston *et al.*, 1997; Zhang, 1999). Microblade technology increases dramatically in frequency in the stratified Pigeon Mountain sequence between 13,510 ± 136 (Beta 86731) 11,608 ± 183 (Beta 86732), coinciding with the Younger Dryas (Elston *et al.*, 1997; Madsen *et al.*, 1998).

There is a gap in the archeological record of northwest China between the end of the Younger Dryas (ca. 11.5 ka) and the emergence of agricultural adaptations on the western Loess Plateau, shortly after the Holocene climatic optimum at 8200 Cal yr BP (Bettinger *et al.*, this volume). Initial low-level agricultural activities at sites such as Dadiwan (N35.01, E105.91, 1,500 m.a.s.l., 7800 Cal yr BP) are, within a millennium, converted into intensive agricultural adaptations focused around large, complex permanent settlements associated with Yangshao (6900–5300 Cal yr BP) and Majiayao (5300–4200 Cal yr BP) Cultures (An *et al.*, 2004). The rapid transition from warm–semi-arid to warm–arid conditions around 4000 Cal yr BP may have driven a reduction in the total number and distribution of agricultural settlements over the western Loess Plateau (An *et al.*, 2005). Nomadic pastoralism appears to have become a viable alternative to rain-fed agriculture sometime during the Qijia (ca. 4300–3900 Cal yr BP) (Flad *et al.*, this volume).

6. Archeological Characteristics of the Colonizers

Lenghu locality 1 is the only site for which there is any reliable geochronological evidence for a pre-H2 occupation of the middle-elevation step of the Plateau. There is no evidence for an occupation of this age on the high-elevation step. The very small archeological assemblage, consisting of two cores and a large blade, is minimally consistent with the character of the Early Upper Paleolithic in the source area. On the basis of a fine-grained green–gray quartzite, the two cores show a flat-faced geometry with emphasis on linear blade production. The single blade, also on the same raw material, is large flat and slightly convergent (Fig. 7). It has a faceted platform and retouch along both edges. The Lenghu specimens are typologically linked to the Levallois-like blade technology seen Shuidonggou and other Early Upper Paleolithic occurrences in northeast Asia (Brantingham *et al.*, 2001a; Gao *et al.*, 2004). By contrast, Xiao Qaidam, the other middle elevation site for which a pre-H2 date has been suggested, presents a generic quartzite core-and-flake

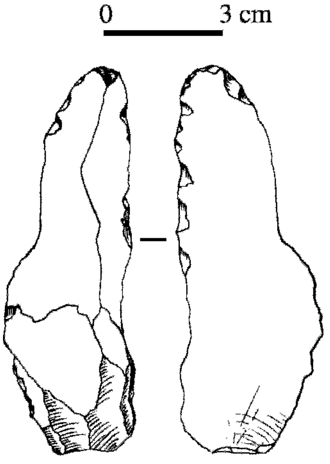

Fig. 7. An Early Upper Paleolithic levallois-like blade from Lenghu locality 1.

technology that is not chronologically diagnostic. We regard these tools as possibly Late Holocene in age based on an association with Han Dynasty age ceramics seen in the nearby Iqe (Yucha) river valley (unpublished field observations). No additional evidence is available to try and characterize the subsistence, mobility and settlement strategies of pre-H2 foragers on the Plateau.

Beyond the site of Chusang (Quesang), far to the south, there are no other candidate archeological occurrences on either the middle- or high-elevation step of the Plateau that can be assigned to the period between H2 and H1 (ca. 24.2–15.8 ka). Aside from the several hand and footprints, Chusang has produced a single probable hearth feature, but no associated stone technology or other cultural materials. Putting aside the concerns about the dating of Chusang, the site is of limited utility for discerning the possible archeological characteristics of a LGM occupation. If evidence from the low-elevation source areas of the Plateau is used as a guide, at this time we would expect to see an emphasis on simple bipolar technologies based on moderate to low quality raw materials and possibly a reduction of mobility (Barton, Brantingham, and Ji, this volume). Such technological characteristics are, of course, not chronologically diagnostic, making accurate geochronology and stratigraphic control essential for identifying any H2–H1 occupations on the Plateau.

Postglacial, Late Upper Paleolithic sites on the middle-elevation step of the Plateau are characterized by both formal microblade technologies and a heavy-duty flaked stone component (Madsen *et al.*, 2006). Indeed, this association is as firmly established here as at sites in low-elevation source area contexts (Elston *et al.*, 1997; Madsen *et al.*, 1998). It is also in this context that we have our first direct evidence from the Plateau of both subsistence activities and within-settlement patterning of activities. Jiangxigou 1, ca. 14.7 ka, on the southern shore of Qinghai Lake, preserves at least two simple, unprepared hearths or hearth-related features with associated cultural debris. The first feature is a 50 cm long, 2 cm thick lens of charcoal-stained sand with no underlying fire-reddening. What is preserved may represent a secondary concentration of debris raked from a true hearth that may have eroded away. Two pieces of microdebitage related to microblade production were recovered from within the concentration of debris. A complete microblade and two mid-section fragments of long bones from a gazelle-sized animal were recovered from the face of the aeolian sand 5 m east of the hearth.

The other simple feature at Jiangxigou 1 consists of a concentration of stream cobbles, broken and burned bone, and charcoal centered on a ~3.5 m diameter use surface ~55 cm below and ~13 m east of the first hearth remnant (Fig. 8). The feature also appears to represent materials raked from a primary hearth. Nevertheless, a comparatively large array of broken and burned bone fragments was recovered. Much of the faunal material consists of small fragments of cancellous bone suggesting it may be associated with bone boiling and degreasing activities (Madsen *et al.*, 2006). None of the lithic specimens from the feature is typologically diagnostic of a specialized core reduction strategy, such as a formal microblade core technology, and no formal retouch tools were recovered. However, that the distribution of flake and flake shatter sizes is strongly suggestive of either preparation of small cores and/or retouching of flake tools. The absence of formal microblades or debitage characteristic of core rejuvenation argues against later stage core reduction directly associated with the exposed portion of the site.

Heimahe 1 (ca. 13.3–12.6 ka) is very similar to Jiangxigou 1 in both site structure and contents, but has yielded more examples of formal microblades. The primary cultural feature is an isolated hearth with a surrounding ash- and charcoal-stained use surface (Fig. 9). Artifacts on this use surface are restricted to an area within 1.8 m of the fire hearth. These include a concentration of possible bifacial thinning flakes, a quartzite core, microblade fragments, a bifacially worked slate scraper, and a possible ground stone cobble. Numerous bone specimens were collected from in and around the hearth. The majority of these are small and fragmentary, and many are burned. Most of the bone fragments are attributable to a medium-sized ungulate, possibly gazelle. Eggshell fragments from hen/duck-sized eggs were also recovered from the

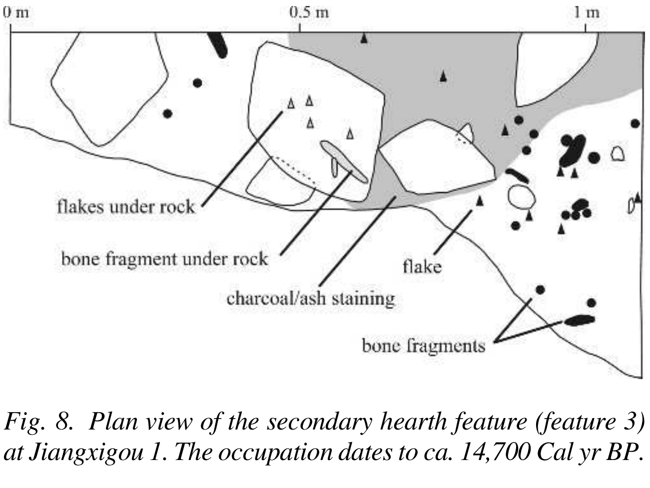

Fig. 8. Plan view of the secondary hearth feature (feature 3) at Jiangxigou 1. The occupation dates to ca. 14,700 Cal yr BP.

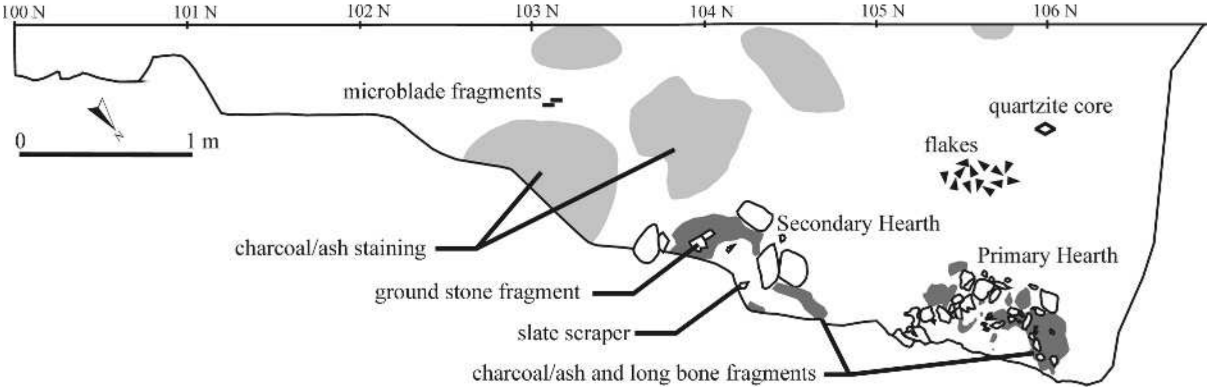

Fig. 9. Plan view of the cultural surface at Heimahe 1. The occupation dates to ca. 13,000 Cal yr BP.

occupational surface. Overall, the simple, unprepared cultural features and small number and diversity of artifacts suggest that Jiangxigou 1 and Heimahe 1 each represent short-term, single-visit foraging camps occupied by a small foraging parties. Subsistence focus seems to have been on the procurement and intensive processing of a gazelle-sized ungulate and possibly on egg collecting (at Heimahe 1).

The Early Holocene sites that are known on the middle- and high-elevation steps of the Plateau are broadly characteristic of the northeast Asian Late Upper Paleolithic or Epi-Paleolithic. These sites contain both a microblade and generalized flaked stone component, but in high elevation contexts we see the addition of a specialized large blade and bladelet technology that appears to be unique to the area (Brantingham *et al.*, 2001b). In the Qinghai Lake basin, the site of Heimahe 3 (N36.71, E99.78, 3202 m.a.s.l.) is virtually identical to Jiangxigou 1 and Heimahe 1 in the structure of the site and included cultural materials, despite its Early Holocene age of 8450 ± 50 Cal yr BP. A single, unprepared hearth is associated with fragmentary bone and generalized flaked stone tools (Fig. 10). Formal microblades are present in very small numbers. It would appear that short-term foraging camps focused on procurement and processing of a gazelle-sized ungulates remained part of the settlement system of populations on the middle step of the Plateau until at least the Holocene cold-dry event at ca. 8200 Cal yr BP.

We lack specific information about the subsistence strategies of populations on the high-elevation step of the Plateau at this time. However, the lithic assemblages attributed to the Early Holocene are particularly rich, allowing us to draw a number of important inferences about the nature of high elevation adaptations at this time. The Xidatan 2 lithic assemblage is diverse both in terms of raw material types and technologies represented. Seven broad classes of raw material are present in the assemblage, including a chemically distinctive true obsidian glass (Brantingham *et al.*, in prep). Raw material source locations are known for two of these materials. A light yellowish brown to grayish brown mudstone originates from deposits around active springs at the Police Station 1 and 2 archeological sites in the Kekexili nature reserve (N35.43 and E93.61), approximately 66 km away. Obsidian artifacts chemically identical to that from Xidatan 2 have been identified at four other archeological sites on the Plateau. Three of these sites are on the high Plateau, south of Xidatan 2, but one (Jiangxigou 2) is on the south shore of Qinghai Lake. The geological source of this material is known to be centered around Migriggyangzham Co (N33.42, E90.30, 5240 m.a.s.l.) (Brantingham *et al.*, 2001b).

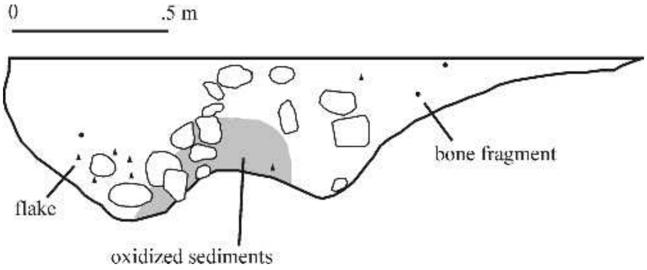

Fig. 10. Plan view of the cultural surface at Heimahe 3. The hearth and associated materials are dated to ca. 8450 Cal yr BP.

The Xidatan 2 lithic assemblage includes pieces representative of core reduction, but very few specimens recognized as formal retouched tools (Fig. 11). Cores are classified as either generalized flake technology or classic northeast Asian microblade cores (see Elston and Brantingham, 2003). One exception to this pattern is a series of bifacial discoid cores that were prepared to produce circular flakes that were then retouched around all or part of the margin (Brantingham *et al.*, in prep). These cores were not organized around a Levallois geometry, but nevertheless were designed to produce flakes of standardized size and shape.[2] Generalized flakes and microblades are the two most common flake types at Xidatan 2. However, bipolar technology makes up a small, but distinctive component of both the flake assemblage and flake shatter and it is not unlike that seen in low elevation

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[2] A core refit from Xidatan 2 shows that core reduction begins with preparation of a bifacial discoid which is then struck parallel to the plane of intersection between the faces to detach tablet-like, circular flakes. This technology shares much in common with the technique for microblade core platform rejuvenation and we suspect that the origin of this discoidal prepared core reduction process is derived from Northeast Asian microblade technologies, though it is applied to a large flake-core substrate.

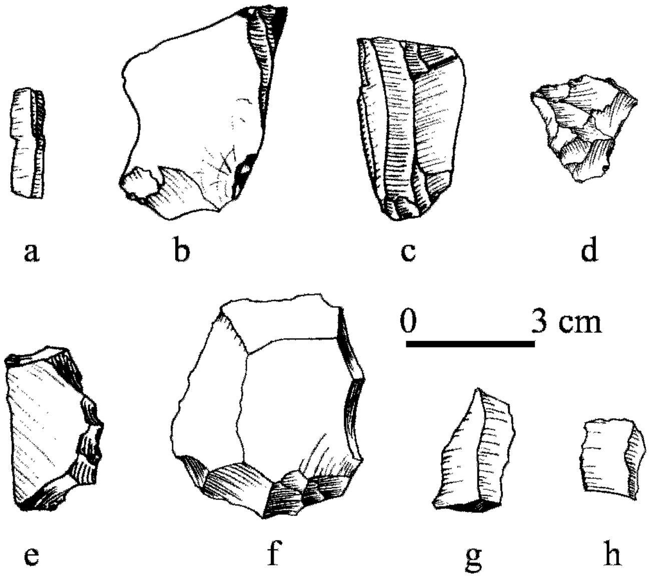

Fig. 11. Lithic specimens from Xidatan 2 (a–e) and the Police Station 1 site in the Kekexili nature reserve (f–h). a, microblade; b, microblade core perform on fined-grained gray quartzite; c, microblade core on cream-colored mudstone from the Police Station 1 spring deposits; d, heavily retouched flake made on Chang Tang obsidian; e and f, flat, tablet-like flakes removed from the face prepared discoidal cores made on gray–green quartzite and Police Station mudstone; g and h, distal and medial bladelet segments.

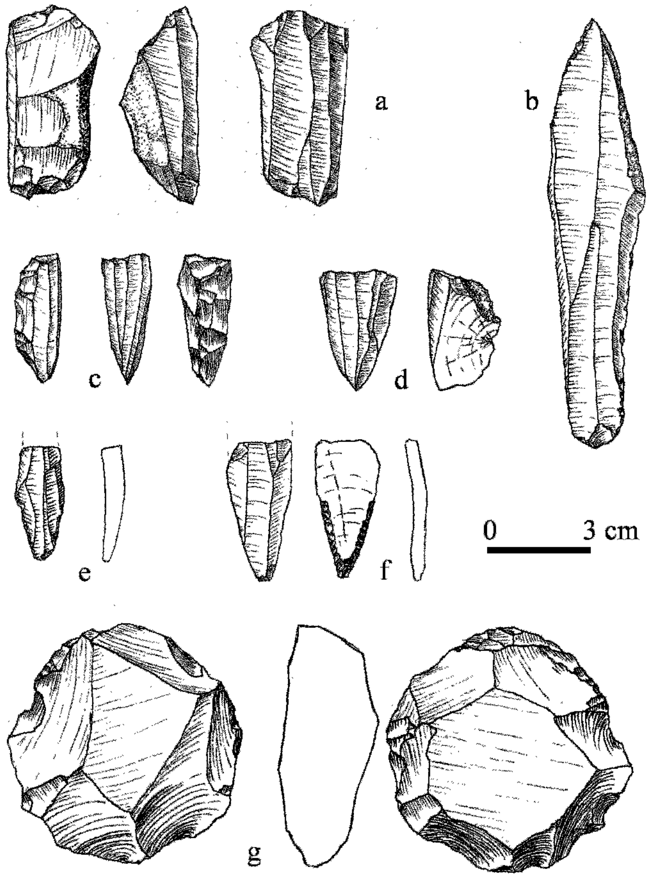

Fig. 12. Lithic specimens from the Chang Tang nature reserve. a, bladelet core; b, pointed prismatic blade; c and d, flake-based microblade cores; e and f, proximal bladelets with retouched hafting accommodations; prepared discoidal core used for producing tablet-like circular flakes.

contexts during the LGM (Madsen *et al.*, 2001) (Barton, Brantingham, and Ji, this volume). Only 3 percent of the total assemblage preserve evidence of formal retouch and two of the specimens are based on Plateau obsidian. Two remaining retouched specimens should technically be classified as debitage; these are burin-like spalls that preserve scraper-like retouch along one side and are most likely byproducts of tool resharpening. Overall, Xidatan 2 provides good evidence for the continued use of a formal microblade technology, most probably as part of composite points, well into the Early Holocene. The distribution of debitage size classes at the site suggests that retooling activities were taking place here, while the topographic position of the site in a steep cut canyon would have been an ideal setting for game drives.

Equally important is the link that Xidatan 2 provides with other undated sites present on the high Plateau, most notably the numerous surface assemblages from the Chang Tang reported by Brantingham, Olsen *et al.* (2001b) and several sites in the Kekexili nature reserve. These sites preserve the same formal microblade technology seen at Xidatan 2 made on a similarly diverse range of raw material types. At least one of the Chang Tang sites (Tsatsang) also contains an example of the unique discoid prepared core technology seen at Xidatan 2. The Chang Tang assemblages are unique, however, in preserving a specialized large blade and bladelet technology (Fig. 12). The blades are extremely flat, have very straight or gradually convergent edges and "punctiforme" striking platforms. Several specimens preserve lateral retouch along the margins and ventral retouch at the base, which appears to represent a special accommodation for end hafting of the blades possibly as spear points. Importantly, these blades are technologically very different from the Levallois-like flat-faced blade technology seen at Shuidonggou and other northeast Asian Early Upper Paleolithic sites. The uniqueness of this technology led Brantingham, Olsen *et al.* (2001b) to speculate that they were LGM in age. However, the striking technological similarity of the entire collection of Chang Tang materials to the Xidatan 2 assemblage, as well as the presence of Chang Tang obsidian at Xidatan 2, two of the Kekexili sites and one of the Chang Tang sites, leads us now to conclude that the Chang Tang assemblages are all Early Holocene in age, contemporaneous with Xidatan 2.

The distribution of Chang Tang obsidian on the Tibetan Plateau also reveals something important about the organization of high-elevation habitat exploitation during the Early Holocene. Xidatan 2 is approximately 416 km from the source of the obsidian at Migriggyangzham Co. The

Dogai Coring, Erdaogou and Police Station 1 sites are 171, 243, and 350 km from the source and are 495, 177, and 66 km away from Xidatan 2, respectively. Amazingly, this same obsidian has been recovered from the Jiangxigou 2 site, on the southern shore of Qinghai Lake, 551 km from Xidatan 2 and 951 km from the known source. It is presently unclear whether the obsidian from Jiangxigou 2 is associated with the 9 or 5 ka date there. However, the correlation with Xidatan 2 argues for the earlier age. In any case, the presence of this raw material on the middle-elevation step suggests that movement of populations between high- and mid-elevation areas was established as early as 8 ka, but perhaps not earlier. On these grounds, we now favor assigning Early Holocene ages to one other middle-elevation step bladelet- and/or microblade-dominated surface assemblages. The Da Qaidam surface locality is located on a well-formed beach ridge in the Da Qaidam basin (N37.76, E95.26, 3110 m.a.s.l.). Previously, we had speculated that the beach represented a high stand of the Da Qaidam during MIS 3, possibly corresponding to the warm-wet event following H3 (ca. 30.5 ka) (Brantingham *et al.*, 2003). The technological character of the Da Qaidam lithic assemblage is identical to that seen at Xidatan 2 as well as the Chang Tang and Kekexili localities. The assemblage is similarly diverse in terms of raw material types. If this age assignment withstands further scrutiny, then Da Qaidam would further support the conclusion that regular movement between the middle- and high-elevation steps of the Plateau was established by the Early Holocene. However, we cannot yet conclusively trace any of the Da Qaidam stone raw materials to a high-elevation step source, unlike at Jiangxigou 2.

The earliest evidence for nonforaging adaptations on the Tibetan Plateau is found at the site of Karou and dated to ca. 5758 ± 109 Cal yr BP (CPAM, 1985; Aldenderfer and Zhang, 2004). Formal architecture consisting of several semisubterranean buildings with central hearth features, storage pits and an incredibly rich assemblage of ceramic, chipped stone, and ground stone technologies is recognized, even in the earliest occupations at Karou. Cultivated millet has been identified at the site as well as possibly domesticated pigs. A range of hunted animals (e.g., red deer and roe deer) and gathered plant foods are also recognized (see Aldenderfer and Zhang, 2004). While an Early or Middle Holocene site of this size and complexity has yet to be identified on the northern Plateau, the site of Jiangxigou 2 (ca. 9–6 ka) preserves thick midden deposits with abundant charcoal, ash, fragmentary bone, chipped stone technologies, and at least two varieties of ceramics (a thick plain ware and a think cord marked ware). The highly fragmentary faunal assemblage includes deciduous dentition attributed to sheep as well as a small gazelle and small cervid. While it is presently uncertain whether the sheep remains represent wild or domesticated animals, the presence of gazelle and cervid remains suggests that hunting of wild game remained important through the Early Holocene. With a minimum age of 5587 ± 60 and maximum of 9140 ± 90 ka, these materials are nearly as old if not older than that seen at Karou.

7. Evaluating Colonization Models

The available archeological evidence from the Tibetan Plateau and surrounding low-elevation source areas is sufficient to provide a preliminary evaluation of the three alternative colonization models outlined at the beginning of this chapter. We propose that colonization can be driven by a process of (1) adaptive radiation, where the appearance of new adaptations in low-elevation source areas drops the hard biogeographic barrier preventing movement into high-elevation regions and low-elevation adaptive traits are sufficient to ensure survival in the high-elevation area; (2) directional selection, where initial forays into high-elevation areas are supported by low-elevation adaptations, but it is selection within the high-elevation environment that drives the appearance of unique adaptive characteristics that ensure survival; and (3) competitive exclusion, where the evolution of superior adaptive strategies in low-elevation environments pushes populations retaining ancestral adaptations into suboptimal high-elevation habitats.

All three colonization models require that there be a metapopulation present in the low-elevation areas surrounding the Tibetan Plateau to serve as a source of potential colonists. This seems like a trivial observation. However, several research groups have argued for massive depopulation of northeast Asia, including north China, during Pleistocene glacial events (Goebel, 2004; Brantingham *et al.*, 2004a). Barton *et al.* (this volume) use radiocarbon evidence from north China to show that occupation intensity in the low-elevation source areas of the middle- and high-elevation step of the Plateau fluctuated, but also that the area was never completely abandoned, at least over the last 40 ka (Fig. 13). The aggregate radiocarbon record for north China shows, in fact, that increases in the summed probability density distribution of calibrated radiocarbon dates tends to coincide with extreme climatic events, particularly H3 (ca. 30.5 ka), H1 (ca. 15.8 ka) and the Younger Dryas (ca. 12.8–11.5 ka). While the interpretation of such data is not unproblematic, it may provide a rough guide as to the intensity of archeological site formation at different times.

Present evidence supports the adaptive radiation of populations onto the Tibetan Plateau during three distinct periods, before H2, between H1, and the Younger Dryas and again in the Middle Holocene around 6000 Cal yr BP (Fig. 14). Occupation of the high-elevation step during the Early Holocene displays characteristics consistent with both competitive exclusion and directional selection, possibly in that sequence.

The evidence for the presence of human groups on the middle-elevation step of the Plateau before H2 (ca. 24.2 ka) is arguably limited. Only Lenghu locality 1 is found in a date-constrained surface setting with a minimum age greater than H2 (ca. 24.2 ka), maximum age of less than H4 (ca. 38.8 ka) and a probable age of 28–30 ka, immediately after H3 (Fig. 13). The Lenghu materials may thus be the same age as or slightly younger than the oldest Early Upper Paleolithic assemblages known in northwest China (Madsen *et al.*, 2001; Brantingham *et al.*, 2001a) (Barton, Brantingham, and Ji, this volume). The fact that the Lenghu materials

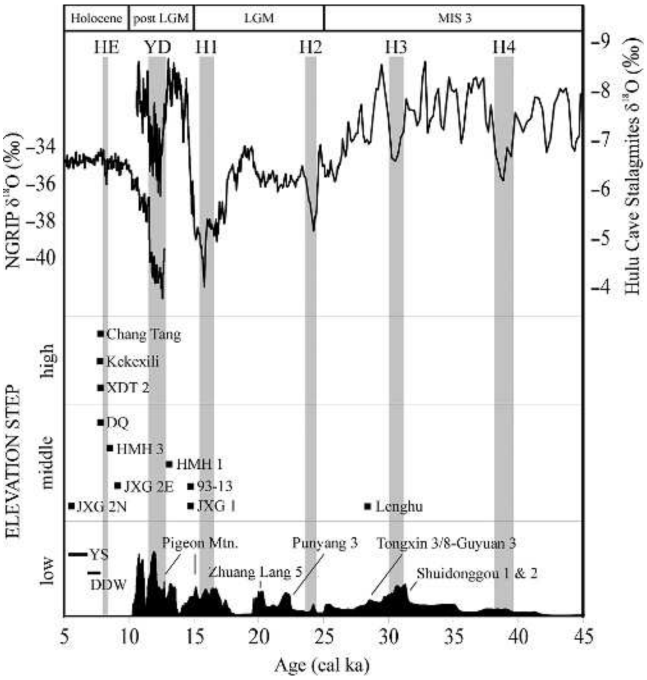

Fig. 13. Ages of sites and their positions within the low-, middle-, and high-elevation steps of the Tibetan Plateau. Individual radiocarbon sites from within the low-elevation step source area are shown against the summed probability density function for all known radiocarbon dated sites in North China (see Barton, Brantingham and Ji, this volume). Sites/Culture groups: DDW, Dadiwan Neolithic; YS, Yangshao Neolithic; JXG 1, Jiangxigou Locality 1; HMH 1 and 3; Heimahe 1 and 3; JXG 2E, earliest occupation at Jiangxigou 2; JXG 2N, Neolithic occupation at Jiangxigou 2; DQ, Da Qaidam; XDT 2, Xidatan 2. Kekexili includes the Police Station 1 and 2 and Erdaogou sites. Chang Tang includes all of the sites described in Brantingham, Olsen et al. (2001).

consist of stone technologies that are identical to the Levallois-like flat-faced blade technologies seen at Shuidonggou and other Early Upper Paleolithic sites in the region lends support to a 28–30 ka age assignment. Overall, the appearance of Early Upper Paleolithic blade technologies on the middle-elevation step of the Plateau is consistent with an adaptive radiation model for colonization: specialized large blade technologies appear first in low-elevation source areas and subsequently in high-elevation recipient areas with no apparent modification. The emergence of the Early Upper Paleolithic appears to have lowered, at least partially, the biogeographic barrier to human movements onto the middle-elevation step of the Tibetan Plateau. Selective pressures operating within low-elevation environments are thus responsible for changes in human biogeographic capacities at this time.

While there is no reliable evidence for human occupation anywhere on the Plateau between H2 and H1 (ca. 24.2–15.8 ka), there is growing evidence for a significant presence of human groups on the middle-elevation step during the postglacial period. These groups appear to have made use of specialized microblade technologies, like those seen over a wide area of northeast Asia, as well as more generic, heavy-duty chipped stone tools and simple hand-held grinding equipment (Madsen *et al.*, 2006). Sites in the middle-elevation step Qinghai Lake basin, which predate the Younger Dryas (Fig. 13), represent short-term foraging camps where intensive processing of medium- and small-sized game took place around simple hearth features (Madsen *et al.*, 2006). The appearance of Late Upper Paleolithic adaptations on the middle-elevation step of the Plateau with little or no apparent modification, shortly after their emergence in greater northeast Asia, is strongly suggestive of a process of adaptive radiation. Low elevation selective pressures drove the emergence of the Late Upper Paleolithic and these adaptations (further) lowered the barrier to population movements onto the Tibetan Plateau.

The situation may have been quite different during the Early Holocene. At this time we see the first unequivocal evidence for exploitation of the high-elevation step of the Plateau. Buried archeological materials at Xidatan 2 are dated between ca. 8.2–6.4 ka and have a probable age of ca. 7.8 ka. The Xidatan 2 assemblage is broadly similar to the Late Upper Paleolithic in low-elevation environments. Shared technological attributes and stone raw material types link sites in the Kekexili and Chang Tang to Xidatan 2. We now believe that the Kekexili and Chang Tang surface assemblages are all also Early Holocene in age (contra Brantingham *et al.*, 2001b).

If these high-elevation sites are linked to dedicated, full-time foragers, then it is possible to invoke a model of competitive exclusion to explain some of their archeological characteristics and temporal–spatial pattern of distribution (Fig. 14). Xidatan 2 was occupied at a time when early agricultural adaptations were coming to dominate landscapes within the low-elevation source areas around the Plateau. The Dadiwan Neolithic appears on the western Loess Plateau abruptly around 7800 Cal yr BP, but the initial steps towards a fully fledged agricultural adaptation should precede this date by several centuries, if not several millennia (Bettinger *et al.*, this volume). By 6800 Cal yr BP intensive settled agricultural communities are found over a widespread area of north and northwest China, all of which are generally assigned to the early Yangshao (early Banpo) (Chang, 1986; Underhill, 1997; Lu, 1999; An *et al.*, 2004; An *et al.*, 2005). We believe that the emergence of agricultural adaptations in the low-elevation areas surrounding the northern Tibet Plateau and appearance of the first well-dated examples of human exploitation of the high-elevation step of the Plateau at the same time is not coincidental. Both events follow the Holocene cold-dry event (ca. 8200 Cal yr BP) falling within the regional climatic optimum. In low-elevation environments, warm-wet conditions during the Early Holocene were good for seasonal plant productivity, specifically on river floodplains, and may have contributed to the feasibility of agricultural specialization (Bettinger *et al.*, this volume; Richerson *et al.*, 2001). In high-elevation environments, these same warm-wet conditions may have stimulated the expansion of mesic (as opposed to arid) steppe-grasslands

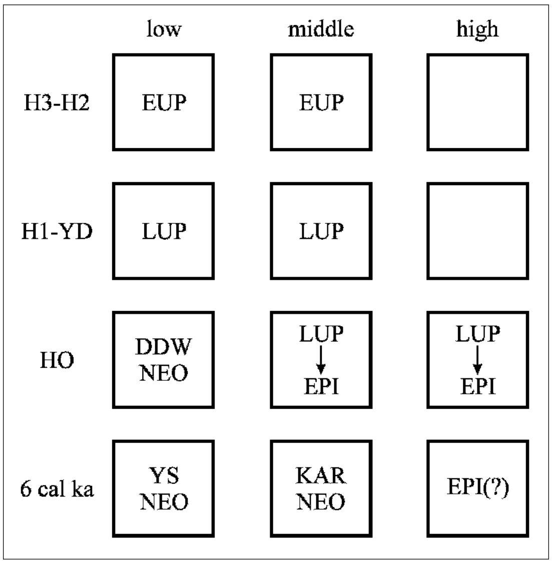

Fig. 14. Repeated colonization of the Plateau between H3 and H2, between H1 and the Younger Dryas and again approximately 6 Cal ka are each consistent with adaptive radiations based on largely unmodified low-elevation adaptations. The appearance of epi-Paleolithic groups on the middle- and high-elevation step are more consistent with an iterated process of colonization beginning with competitive exclusion of Late Upper Paleolithic from low-elevation environments and followed by directional selection leading to a unique high-elevation adaptive complex. The adaptive radiation of agricultural populations onto the middle-elevation step of the plateau ca. 6 ka MAY have eliminated epi-Paleolithic populations from the plateau. Abbreviations: YD, Younger Dryas; HO, Holocene optimum; EUP, Early Upper Paleolithic; LUP, Late Upper Paleolithic; EPI, epi-Paleolithic; DDW NEO, Dadiwan Neolithic; YS NEO, Yangshao Neolithic; KAR NEO, Karou Neolithic.

and game populations would have flourished. Climatic, environmental and regional population conditions thus may have favored the displacement of foragers onto the Plateau. Filling of low-elevation environments with agricultural populations may have pushed foragers up onto the Plateau, with the pull of a reasonably rich faunal community during the Holocene optimum also playing some measured causal role. Ethnohistoric evidence suggests that foragers who, for whatever reason, decide not to adopt new subsistence and social strategies are likely to be pushed into increasingly marginal environments (Spielmann and Eder, 1994). While these "relict" foragers may come to establish resource-exchange relationships with agriculturalists and/or pastoralists who occupy prime habitat, these relationships tend to be highly asymmetric and it is clearly the foragers who suffer the far more severe conditions (e.g., Howell, 2000). In sum, Late Upper Paleolithic adaptations prevalent in low-elevation environments surrounding the Plateau, during and immediately after the Younger Dryas (ca. 12.8–11.4 ka), may have provided some entrance into high-elevation environments. However, competitive exclusion from low-elevation environments by early farming populations may have been responsible for making occupations on the high Plateau more permanent.

Several features of the assemblages seen on the high-elevation step of the Plateau suggest, however, that competitive exclusion was not the only process at play in driving Early Holocene colonization. Large, flat blade and bladelet technologies of the Chang Tang are derived from a Late Upper Paleolithic substrate, but present attributes that are unknown in the low-elevation environments that surround the Plateau. First, although these blade products tend to be quite large, they appear to have been produced by either indirect percussion or pressure flaking; a method used in northeast Asia for the manufacturing of microblades, but not regularly for large blades. Second, retouch patterns on some of the Chang Tang specimens seem to suggest that large blades and bladelets were sometimes end-hafted as spear points, also a pattern unseen in the Early or Late Upper Paleolithic of northeast Asia. Finally, stone raw material transport patterns appear to represent stone procurement distances that are at least an order of magnitude farther than anything previously documented in the Paleolithic of northeast Asia. Most instance of stone raw material procurement seen in the Early and Late Upper Paleolithic of north and northwest China are of low- to moderate-quality raw materials that are usually available in the immediate vicinity of the sites where they were worked and discarded. On the northern Tibetan Plateau, during the Early Holocene, we can demonstrate the transport of obsidian tool stone over distances as large as 951 km – between the source locality along the Kekexili–Chang Tang frontier and the Qinghai Lake site Jiangxigou 2. All of these features lead us to suggest that the Early Holocene lithic assemblages from Xidatan 2, Kekexili and the Chang Tang represent uniquely evolved strategies linked to the extreme selective pressures of high-elevation environments. Why these selective pressures did not appear to impact earlier incursions onto the middle-elevation step of the Plateau remains an open question. The answer may lie, however, in the observation that directional selection during the Early Holocene may have followed immediately on the heals of a period of competitive exclusion that necessitated more permanent occupation of the Plateau (Fig. 14).

Finally, we note that the appearance of fully fledged agricultural settlements on the Plateau after 6000 Cal yr BP appears to reflect another period of adaptive radiation from low-elevation source areas to middle-elevation sites. In this case, however, the evidence clearly points to the successful establishment of full-time, year round occupations. Karou, for example, shows the use of permanent architecture, storage features and domesticated plants and animals. Less is known about Jiangxigou 2 at Qinghai Lake, but the presence of large accumulations of debris (ash, rock, and animal bones) and the use ceramic vessels suggests lengthy, if not permanent occupation. The impact of this adaptive radiation on resident populations, if they were present, is unknown.

8. Seasonal Exploitation or Year-Round Occupation?

Each of the biogeographic models examined here has the requirement that dispersal leads to an established population on the Plateau. Otherwise we must acknowledge that a biogeographic barrier to colonization remains in place. From an archeological standpoint, we are presented with the difficult task of assessing whether archeological sites found on the Plateau represent continuous, year-round occupation, or merely seasonal exploitation of high-elevation habitats (see Derevianko *et al*., 2004).

Human populations are recognized on the middle-elevation step of the Plateau at ca. 28–30 ka and 13–14.5 ka shortly after the initial appearances of Early and Late Upper Paleolithic in low-elevation source areas, respectively (see Fig. 13). However, we cannot be certain that the sites on the Plateau at these two different times represent anything more than specialized seasonal foraging forays. The Late Upper Paleolithic Qinghai Lake sites (14.5–13 ka) have simple hearth features, but there is no evidence for formal architecture, storage features, or large quantities of accumulated debris that would indicate long-term utilization of the area. The Qinghai Lake sites seem to represent short-term encampments that were used for at most only a few days. We note also that Lenghu (ca. 28–30 ka) and Qinghai Lake sites are close to the margins of the Plateau and near major mountain passes leading between the low- and middle-elevation steps. The linear distance from Lenghu to low-elevation areas below 2500 m.a.s.l. is less than 65 km, while it is less than 100 km in the case of the Qinghai Lake sites. Such distances were easily traversed by Holocene and more recent foragers in the Great Basin as part of seasonal foraging activities (e.g., Zeanah, 2004). The most parsimonious explanation is that the Early and Late Upper Paleolithic sites on the middle-elevation step of the Tibetan Plateau represent seasonal exploitation only. On technical grounds, therefore, we must qualify our conclusions that Early Upper Paleolithic and Late Upper Paleolithic human presence on the Plateau represents a process of adaptive radiation. Certainly, these adaptations allowed for seasonal exploitation, but perhaps no more. This is an important distinction since seasonal exploitation is unlikely to entail the severe demographic costs of year-round occupation and selection – both in terms of strict natural selection as well as within a cultural evolutionary framework (Boyd and Richerson, 1985) – is therefore unlikely to have had much scope for operation.

It is similarly difficult to argue conclusively that Early Holocene (ca. 7800 Cal yr BP) occupations of the middle- and high-elevation steps of the Plateau represent more than seasonal patterns of exploitation (see Fig. 13). The primary evidence in favor of full-time, year-round occupation of the high-elevation step of the Plateau at this time relates to the sheer size of the territory exploited. In contrast to the pattern of Early and Late Upper Paleolithic sites on the middle-elevation step being situated near direct access to corridors leading to low-elevation areas, many of the Early Holocene surface archeological sites in the Kekexili and Chang Tang are hundreds of kilometers from any point of descent. Whether or not long distances mobility reflects seasonal or year-round occupation is in large measure dependent upon what we assume about the organization of mobility and the associated costs of movement (Brantingham, 2003; Brantingham, 2006). The cumulative distance traveled by arctic foragers over an annual round of residential moves may reach 600–700 km (Kelly, 1995). Given the potentially high costs of mobility at high elevation (Aldenderfer, 1998, this volume), it is reasonable to hypothesize that the Kekexili and Chang Tang sites represent year-round occupation. However, there is also good evidence stretching back as far as the Middle Paleolithic that stone raw materials were regularly transported over distances of 300–400 km and occasionally as much as 800–1000 km (Féblot-Augustins, 1997b), presumably in single logistical foraging forays. This latter argument leaves open the possibility that long-distance moves were regularly made onto and off of the high-elevation step of the Plateau. In possible support of this alternative hypothesis we note occurrence of Chang Tang obsidian at the Qinghai Lake site of Jiangxigou 951 km away as the crow files. Regardless of whether this long-distance transfer represents direct or indirect procurement of stone, it demonstrates that around 6–8 ka groups of people were moving between the middle- and high-elevation steps of the Plateau at least on occasion.

A more theoretically based argument for the establishment of year-round occupation around 6–8 ka would point to the unique character of the lithic technologies present at Xidatan 2 and the Kekexili and Chang Tang sites. If the specialized large blade and bladelet technologies and strategies for end hafting of large, pointed blade blanks represent a process of directional selection, then this requires sufficient exposure to selective pressures to drive change. Given the absence of such directional changes during Early and Late Upper Paleolithic incursions onto the Plateau, their presence during the Holocene suggests a much greater exposure to selection, perhaps through year-round occupation.

The only unequivocal evidence for year-round occupation of the middle-elevation step of the Plateau postdates 6000 Cal yr BP and is associated with the adaptive radiation of agricultural groups out of low-elevation areas. The site of Karou and possibly Jiangxigou 2, both at ca. 3100–3200 m.a.s.l., represent this radiation. Madsen *et al.* (in press) have hypothesized, based on this evidence, that full-time, year round occupation of even higher elevation areas in Kekexili and the Chang Tang may not have been possible without radical adaptive innovations, such as Yak domestication (Rhode, this volume), or creation of large social networks that supply resources to populations in the most marginal habitats. Although this suggestion is controversial, it is consistent with the evidence that is currently available.

Ultimately, however, additional evidence must be brought to bear on the problem of when full-time, year-round occupation of the Tibetan Plateau was finally established. If such occupations were possible through a strict foraging adaptation, likely focused on specialized large-game hunting, then one would expect to see sites with zooarcheological remains in abundances commensurate with the need for long-term supply (especially at winter camps) and probably also more substantial architectural and for food storage features.

9. Conclusions

We favor the view that the emergence of Early and Late Upper Paleolithic adaptations during pre- and post-LGM time periods, respectively, provided a basis for a limited adaptive radiation of low elevation foragers onto the middle-, but not the high-elevation step, of the Tibetan Plateau. More permanent occupations were more likely established on both the middle- and high-elevation steps around 8200–6400 Cal yr BP, coincident with the Holocene climatic optimum. We argue that the groups moving onto the Plateau at this time were probably dedicated foragers and that the primary cause for this dispersal was competitive exclusion from low-elevation environments that were increasingly filled with settled agriculturalists. We invoke directional selection to explain the appearance of specialized large blade and bladelet technologies in high-elevation step lithic assemblages during the Early Holocene. Such adaptive shifts may have been necessary to ensure year-round survival of populations marginalized to suboptimal habitats on the Plateau. However, there is no conclusive proof that permanent occupations were established above 3000 m.a.s.l. before 6000 Cal yr BP and we have raised the possibility that permanent occupation was in fact impossible without the support of agriculture or full-time pastoralism. It should be relatively straightforward to test certain aspects of these preliminary conclusions in future archeological work. In particular, confident dating of archeological assemblages could easily establish that the adaptive radiations of Late and even Early Upper Paleolithic groups onto the middle-elevation step also entailed movement onto the high-elevation step. Determining whether such occupations were seasonal or year-round will be more difficult, however.

If the broad pattern of colonization of the Plateau presented here is even partially correct then we are confronted with a very different view of the world then presented in studies of contemporary population genetics. To wit, leading geneticists have argued that 30,000 years of occupation at high elevation may have been necessary for microevolutionary processes to generate the specialized physiological capacities seen among contemporary Tibetan populations (Moore *et al.*, 2000; Beall, 2001). The conclusion that full-time occupation was not established before 8200 Cal yr BP suggests either that (1) the populations that initially colonized the high-elevation areas of the Tibetan Plateau possessed genetic variability that predisposed them to rapid accumulation of the physiological adaptations that we see today or (2) that selection in high-elevation environments is far more severe than generally thought and these strong selective pressures drove rapid adaptation. While we favor emphasizing the second mechanism, there may be some truth to the suggestion that initial colonizing populations were genetically unique in some way. The fact that Tibetan and Andean populations appear to have evolved different physiological strategies for dealing with the stresses of life at elevation suggests differences in initial conditions, rather than major differences in the selective pressures experienced.

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10

Modeling the Neolithic on the Tibetan Plateau

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Abstract

Although much remains to be learned of the Neolithic of the Tibetan Plateau, enough is known to develop a set of models on the advent of the Neolithic on the plateau that can be used to guide future research. More sophisticated models are required because most existing models fail to consider the environmental context of the advent of the Neolithic, the nature of constraints on the movement of people and potential domesticates onto the plateau, and finally, the anthropological context of trait diffusion and movement. In this paper, I review existing models as well as what is known of the paleoenvironments of the Tibetan Neolithic and argue that future models must include consideration of different modes of food production, other routes onto the plateau, the biological and physiological constraints on potential plant and animal domesticates, and the evolution of dietary preferences.

1. Introduction

We know more about the Neolithic on the Tibetan Plateau than any other archeological era, but unfortunately, the reality is that we know very little about it at all. Only two sites – Kha rub (Chin. Karou) and Chugong (Chin. Qugong) – have been excavated thoroughly, and while a number of other sites have been tested and dated, it remains the case that we only have the barest of outlines of what the Neolithic is on the plateau (Aldenderfer and Zhang, 2004, pp. 26–40). Obviously, if our empirical data are limited, our understanding of the processes of how Neolithic cultures developed on the plateau is even more incomplete. But it is precisely this lack of knowledge that may provide us with an opportunity to better our understanding of the Tibetan Neolithic and that is through the development of models of process that can direct future excavations and analyses. It is well known that Chinese, thus Tibetan, archeology has been primarily historiographic in its orientation, and problem-oriented research as it is known in the West is virtually unknown. In the case of the Neolithic, for example, this has meant that what archeology has been done on the Tibetan Neolithic has been content to define it as a "stage" of cultural development or progress with little thought about process aside from looking to other, earlier sites elsewhere in China for its inspiration or origins. While this may satisfy a sense of historical narrative, it says little about how the Neolithic on the plateau came into existence and, moreover, what variability may characterize it.

In this paper, following a review of the Neolithic archeology on the plateau and the Holocene paleoclimatic record, I will examine current models that attempt to explain the Tibetan Neolithic and will conclude with a discussion of an integrative approach to modeling the Neolithic on the plateau that considers, among other things, different modes of food production, alternative routes onto the plateau, and data derived from studies of human genetics.

2. What and when is the Tibetan Neolithic?

The Neolithic is traditionally defined by the appearance of sedentary village agriculturalists reliant upon a suite of plant and, sometimes, animal domesticates. The extensive use of pottery is also part of this definition. This is consistent with Underhill (1997. p. 105), who notes that the Neolithic in China is characterized by "...pottery, ground stone tools, sedentism, cultivation, and animal husbandry." If we look strictly at the central plateau (the area comprised today by the Tibet Autonomous Region [TAR], the southern Changtang (Tib. byang tang), and south and central Qinghai), there are three areas that are known to have probable Neolithic-era sites: the valley systems in eastern Tibet, especially the Zachu (Mekong) River near the modern city of Chab mdo (Chin. Chamdo), at the great bend of the Yarlung Tsangpo river as it turns southward, and on the central plateau in the Yarlung and Kyichu valleys (Fig. 1). Additional Neolithic-era sites are found near Lake Qinghai (Ngonpo Tso) and on the extreme northern margins of the plateau in northern Qinghai (Brantingham, this volume). While there are a number of sites known (but as yet undated by some chronometric method) with a material culture on various parts of the plateau consistent with the definition of the Neolithic, the presence of bronze and iron artifacts suggests these are later in time than what is traditionally known as the Neolithic. For example, Aufschnaiter (1956) describes a number of sites approximately 10 km east of

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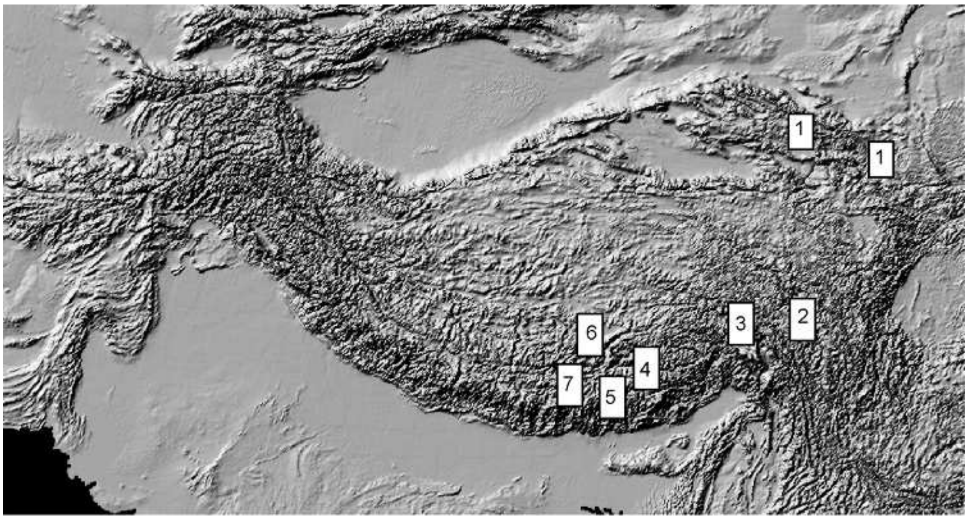

Fig. 1. Location of Neolithic sites on the Tibetan plateau. (1) Qinghai sites; (2) Kha rub and Rngul mdv (Karou and Xioenda); (3) sites at the great bend of the Yarlung Tsangpo; (4) Qinba; (5) Bangga; (6) Chugong (Qugong), Gyaritang; (7) Phrang mgo (Changguogou).

Lhasa on the Kyichu. Excavations in tombs associated with them produced significant quantities of whole ceramics as well as iron knives, arrow points, and other metal objects. Other sites, particularly tombs, which do not have metal but do have ceramics, are abundant on the plateau. Mortuary sites have been examined in some detail, and while some may date to the Neolithic, in the absence of chronometric dating or reliable ceramic typologies, such an attribution is best avoided for the present (Aldenderfer and Zhang, 2004, pp. 33–34).

The two best-known Neolithic sites – Kha rub and Chugong – provide us with a preliminary temporal definition of the Tibetan Neolithic (Table 1). Kha rub is the earliest, and its two major phases of occupation span from ~4000 to 2100 BCE. (5917–4145 Cal yr BP). Chugong, later in time, was occupied from ~1750 to 1050 BCE, although there is

Table 1. Radiocarbon dates of the Tibetan Neolithic.

Site	rcybp	BCE[1]	cal B.P.	Reference
Jiangxigou 2	4850 ± 40		5580 ± 60	Brantingham *et al.* (this volume)
Xidatan 2	5670 ± 40		6460 ± 40	Brantingham *et al.* (this volume)
Kha rub	4955 ± 100		5732 ± 114[2]	Bureau of Cultural Relics (1985)
	4280 ± 100		4841 ± 165[2]	
	3930 ± 80		4372 ± 117[2]	
Chugong		1742-1519		Institute of Archaeology (1999b)
		1688-1457		
		1598-1055		
		1523-1323		
		1414-1162		
		1368-1021		
		1308-930		
Phrang mgo		1370		He (1994) Institute of Archaeology (1999a)
Xioenda	3775 ± 80		4162 ± 130[2]	Sonam Wangdu (1990) Chayet (1994)
Gyaritang	2871 ± 53		3010 ± 82[2]	Nyingcha gyal (personal communication, 2004)

[1] Date calibrated by original author using tree-ring intercepts available at the time of publication, reported as BCE.

[2] Date calibrated by author using OxCal 3.10.

some controversy about the final date of abandonment of the site, which, given the variability in the dates, could be ∼400 years earlier or ∼100 years later. Chronometric dates of the earliest Neolithic cultures from surrounding lowland areas are surprisingly similar in their range, and they overlap substantially with the dates from Kha rub. In Qinghai, on the extreme northeast of the plateau, the Neolithic as defined by the Yangshao archeological culture is dated ∼5000–3400 BCE (Chayet, 1994, p. 51; Aldenderfer and Zhang, 2004, p. 33). However, some have disputed this attribution (see Flad, Yuan, and Li, this volume) and see the Majiayao culture (∼3400–2800 BCE) as the earliest. Slightly further to the south and east of the plateau in Gansu and Shaanxi the earliest Neolithic sites apparently belong the Dadiwan archeological culture which dates ∼6000–5400 BCE, a span significantly earlier than that of the plateau. Finally, in Sichuan, Neolithic cultures are known from ∼5000 BCE (Bureau of Cultural Relics, 1985. p. 178).

What makes Kha rub "Neolithic"? The short answer is that the residential architecture suggests sedentary occupation, there are copious amounts of ceramics, at least one cultivar – millet – is present, and the remains of two animals thought to be domesticated – an unidentified bovid and pigs (*Sus scrofa*) – have been discovered (Flad, Yuan, and Li, this volume). Unfortunately, floral and faunal remains appear to have been haphazardly collected, and further, the analyses of the faunal assemblages were likewise sketchy.

The site is located at 3100 m.a.s.l. on a high terrace above the Zachu (Mekong) River. The total site area was estimated to be 1 ha, of which 1800 m^2 was systematically excavated over two years (1978–1979) by a joint archeological team of Cultural Relics Administration of the TAR and the history department of Sichuan University led by Chinese archeologist Tong Enzheng (Bureau of Cultural Relics, 1985; Tong, 1990). Although the stratigraphy of the site was complex, it could be divided into five (not including the modern ground surface) major stratigraphic complexes, which are said to contain evidence of at least two, and most probably three, distinct occupations of the site. The earliest occupation level (4) contained the remains of seven structures interpreted as domestic residences. Of these, three were rectangular in form and semi-subterranean in construction and ranged in size from 13.8 to 24 m^2 in covered floor area. Two were round or ovoid pit structures, somewhat smaller (10.1–11.4 m^2 areas) with central hearth features. Two other structures were incomplete. In Level 3, many more structures were present. All but one (a roughly ovoid structure partially destroyed by construction) were rectangular and of semi-subterranean construction. Those with central hearth features ranged in covered floor area from roughly 12 to 34 m^2; one structure with what appeared to be multiple rooms or a covered patio had 69 m^2 of floor area. Smaller structures without hearths (presumably small storage facilities) were adjacent to some of these residences. Reconstructions of both the storage and residences suggest that ladders were used to enter and exit them. In Level 2 (said to be the later occupation) was a single complex of three semi-subterranean structures with interior walls composed of rough, uncut stone. Two of these structures (F5 and F12) had a large central hearths and F12 had a bench against one of the interior walls (Bureau of Cultural Relics, 1985, p. 33). Other features on the Level 2 surface include two stone walkways, a large rectangle of stone with of uncertain function, a small stone pen, and circular stone features.

The artifacts recovered from Kha rub are impressive. Ceramic forms are primarily basins, bowls, and jars and are for the most part incompletely fired. Decorative motifs are incised and graved geometric patterns with some appliqué, cord-marking, and basket impressions. One vessel shows traces of black and red paint. The lithic assemblage includes chipped stone tools, debitage, some microliths, and ground stone and polished tools. Flake tools are much more abundant than microliths. Bone tools are abundant as well, and include awls, probable weaving tools, needles, and combs. Decorative objects include stone pendants, jade pins, perforated shells, and stone bracelets. The presence of ceramic spindle whorls indicates textile production, but it is not clear what fiber was being spun.

At least 10 other sites said to be of Neolithic age are found near Kha rub along the Zachu and in the vicinity of Chab mdo (Sonam Wangdu, 1990; Chayet, 1994, p. 46), but of these, only Rngul mdv (Chin. Xiaoenda) has been chronometrically dated (Table 1; Li Yongxian, personal communication, 2004). The site is contemporaneous with the latest occupation of Kha rub.

Despite its importance, the empirical record from Chugong is somewhat limited. No plant remains were described (only a pollen analysis was performed), and simple counts of different animal species were made. According to the excavators, domesticated species encountered included yak (*Bos grunniens*), domesticated sheep (*Ovis aries shangi*), and pig (*Sus scrofa*). No structures were encountered. The ceramic assemblage, however, is large and impressive.

Chugong is located 5 km north of Lhasa at an elevation of 3680 m.a.s.l. (Institute of Archaeology, 1991a, 1991b, 1999b; Huo, 2000). The site is found along the margins of a low hill at the base of higher hills and mountains. The site was heavily eroded and had also suffered damage from local villagers who used the soil of the terrace for construction projects. Portions of the site were also damaged by intrusive tombs. The original extent of the site was estimated to be ∼1 ha, and of this, ∼0.4 ha was excavated. A mortuary component containing 32 tombs is found some 300 m to the northwest. The dates of occupation at the site overlap substantially with the Chinese periodization of early Bronze Age cultures such as Qijia (∼2000 BCE), Siwa (1300–1000 BCE), and Xindian (∼1000 BCE) of Gansu and northwestern China.

The deposit is divided into early and late components. The early component contained only ash pits and three tombs. The later component was defined as one of "redeposition," which in this case appears to mean the reworking of the deposit through time. The ceramic assemblage is described by the investigators as "mature," meaning that many of the vessels are finely made and highly fired (especially when compared to the Kha rub assemblage) and include both hand molded and wheel-thrown examples. Some of the finest ceramics are a highly burnished blackware. However, decoration continues to consist of geometric forms executed by incision, punctation, and some painting. Forms include bowls, jars, and cups. Grinding stones for both subsistence and pigments (red ochre) are common. Bone tools include awls, needles, points, hairpins, combs, and probable weaving implements. Only one bronze artifact – an arrowhead – was recovered from the site. A detailed analysis suggests it is of local origin.

Other sites associated with Chugong and which have had some systematic work include Phrang mgo (Chin. Changguogou), located south of Lhasa on the north bank of the Yarlung Tsangpo at an elevation of 3570 m.a.s.l. (He, 1994; Institute of Archaeology, 1999a; Li and Zhao, 1999), Bangga in the Yarlung Valley (Zhao, 2002), and Qinba (Sonam Wangdu, 1986). Although not radiocarbon dated, the archeological assemblage, especially the ceramics, at Phrang mgo, is very similar to those found at Chugong. Excavations at Bangga have uncovered at least one rectangular semi-subterranean house with 24 m^2 of covered floor area, stone-lined interior storage pits (one of which was used for a secondary burial), and ceramics similar to those at Chugong. Sites thought to be part of the Chugong tradition but which have seen limited work are those in the great bend area (Nying-khri/Nyingchi) of the Yarlung Tsangpo, such as Jumu, Beibeng, and Maniweng, among others (Chayet, 1994, pp. 46–7). More recently, excavations by the Tibet Museum at Gyaritang (4234 m.a.s.l.), located ~130 km northwest of Lhasa along the Yangs pa chan River, have discovered a ceramic and lithic assemblage similar to that found at Chugong, but in an area today that does not support agriculture (Table 1; Nyingcha gyal, personal communication, 2004).

If Kha rub, Chugong, and their related sites are thought to be "Tibetan," the Neolithic cultures in extreme northeastern Qinghai are clearly of lower elevation origin. The dating of Neolithic cultures in this area remains controversial. The Yangshao culture is well known from eastern Gansu and the central Huang He (Yellow) River valley and is said to date between 5000 and 3400 BCE (Underhill, 1997, p. 118). Its presence in Qinghai has been debated, and a local culture, Shilingxia, is said to be its extreme western variant (Chayet, 1994, p. 51). However, it seems more reasonable to regard this culture as an early expression of the following culture, Majiayao (3400–2800 BCE), which is well defined in Qinghai. There are said to be between 20 and 30 small sites in extreme eastern Qinghai that have traces of Majiayao culture, primarily ceramics. This culture is characterized by rectangular semi-subterranean houses, grinding stones, polished stone axes, hoes, large numbers of bone tools, and impressive ceramics painted in red and black with geometric and animal motifs. Sites in Gansu of this culture are known to have broomcorn and foxtail millet as well as hemp fruits. Cemeteries are found near the largest villages, and in the Qinghai sites, burials are secondary and found in wooden coffins. Some burials had significant quantities of painted ceramics accompanying them. The next culture to be found in the region is Banshan (2800–2300 BCE), which is known in Qinghai primarily from the famous mortuary site of Liuwan (Chayet, 1994, p. 53). Burials were accompanied by a wide variety of artifacts, including the famous Banshan ceramics, stone tools (both chipped and polished), bone tools, and some decorative objects, including turquoise, bone, and stone beads as well as stone bracelets. The final Neolithic culture in this region is Machang (2300–2100 BCE). Although best known from Liuwan, there are village sites known from this period in Qinghai, including Machangyan. Subsistence continues to be focused upon millet, and residential structures are similar to those of the preceding cultures. The majority of burials at Liuwan date to this culture, and while burials are generally similar to those of earlier cultures, the ceramics now have significant number of anthropomorphic motifs as well as geometrics that resemble certain characters of early historic writing systems (Chang, 1986, p. 150).

Brantingham and colleagues (this volume) report on the discovery of what they describe as "non-foraging" sites near Ngonpo Tso. The site, Jiangxigou 2, is found near the southern margin of the lake at an elevation of 3310 m.a.s.l. The site is said to contain thick undecorated and thin cord-marked ceramics, but no attribution to any of the Qinghai Neolithic cultures has yet been offered. The materials were found in a well-stratified context, and the authors cautiously note that the ceramics are likely to be associated with a 5580 Cal yr BP radiocarbon assay (Table 1). If this association is valid, this places the site squarely within the Yangshao Neolithic. Another site of Neolithic age but of uncertain dating as well as cultural affiliation is Xidatan 2, located on the extreme northern fringe of the Chang Tang along the Kunlun River at an elevation of 4300 m.a.s.l. Lithic materials, but no ceramics, were found eroding from terrace surfaces. The authors estimate the date of the site at 7800 Cal yr BP (see Table 1).

In summary, a traditionally defined, sedentary village Neolithic begins on the Tibetan Plateau ~4000 BCE and persists at least until ~1100 BCE, a date which in the surrounding lowlands falls into the Bronze Age and is on the cusp of the appearance of more complex societies. The earliest Neolithic, Kha rub, is found on the extreme eastern margins of the plateau, and this provides insight into at least one possible "origin" – from the lowlands in Sichuan or more generally southwestern China, although most archeologists consider it to be a "Tibetan" culture. Chugong, on the central plateau, along with the Neolithic-era sites in the Yarlung and Kyichu valleys and near Nying-khri, is said to be without question an autochthonous expression of the Neolithic and further and is thought to have originated with Kha rub (Aldenderfer and Zhang, 2004, p. 32). Jiangxigou 2 provides another possible Neolithic with clear affinities to the low-elevation northern Qinghai sites and is roughly contemporary with the appearance of Kha rub on the eastern margins of the plateau.

3. Holocene paleoclimates on the Plateau

Before 12.0 ka BP, temperatures across the plateau were uniformly cold, and for the most part, it was relatively arid. After this date, climate shifted to a warmer and wetter regime, which was punctuated by cold and dry periods such as the Younger Drayas. However, local variability in the expression of this climate shift was apparent and was affected by local topography, orography, elevation, and importantly, the degree of northerly penetration of the Indian summer monsoon, which is responsible for as much as 80% of the annual rainfall on the plateau (Herzschuh, 2006). Despite local variability, paleoclimatic records as measured by pollen, stable isotopes, lake level changes, ice core data, and paleosols show that climatic change across the plateau was highly synchronous. However, as He *et al.* (2004) note, climate change on the plateau tended to begin and end earlier than similar events seen at low-elevation sites to the east. The most complete paleoclimatic records on the plateau, obtained primarily from lake cores, are found in far western Tibet at Sumxi-Longmu (also Lungma) Tso (Chin. Co) and Bangong Tso (Gasse *et al.*, 1996), central Tibet at Silling (also Serling) Tso (Gu *et al.*, 1993), Ngoin Tso (Jin *et al.*, 2005), Cuoe Tso (Wu *et al.*, 2006), and Ahung Tso (Morrill *et al.*, 2006), and northeastern Tibet at Ngonpo Tso (Koko Nor, Qinghai Hu) (Ji *et al.*, 2005; (see Fig. 2).

The most significant climate driver in the Early-to-Mid-Holocene was a powerful Indian monsoon, which created warmer and wetter conditions across the plateau after 10,000 years BP. From ~9900 to 6000 Cal yr BP, far western Tibet was warmer and wetter than in modern times (Gasse *et al.*, 1996; Herzschuh, 2006). Lake levels in the region increased, and catchment vegetation changed from montane desert to one dominated by Chenopodaciae and other shrubs. This relatively benign period was punctuated by a short period of aridity and cooler temperatures from 8000 to 7700 Cal yr BP. A trend toward ncreased aridity began at 6000 Cal yr BP, and lower δ^{18}O values imply the end of the Indian summer monsoon influence in the region. Lakes across western and central Tibet begin to become highly saline due to this decrease in precipitation, and vegetation returns to a montane desert assemblage. Maximum aridity reaches its peak ~3800 Cal yr BP, but extremely dry conditions persisted during the period from 3900 to 3200 Cal yr BP, interrupted by minor wet episodes from 3500 to 2500 Cal yr BP. Unfortunately, more precise data on the Late Holocene have not been obtained from these lakes.

Silling Tso is a closed, saline lake found at 4530 m.a.s.l. Gu *et al.* (1993) and Morinaga *et al.* (1993) reconstructed climate based on stable isotope and mineralogical analysis of a single core taken from the southern portion of the lake. A rapid transition from dry-cold to wet-warm conditions begins around 10.0 ka BP, and generally warmer and wetter conditions than the modern era persisted until 4200 Cal yr BP. Lake levels were at their maximum from 8400 to 5500 Cal yr BP, when a gradual increase in δ^{18}O values implies decreased precipitation associated with the weakening of the Indian summer monsoon. This period also shows marked cooling of temperatures. The Late Holocene was characterized by arid and cold conditions, with two peaks – 4200–3300 and 2400–1400 Cal yr BP – separated by brief wet pulses. The latter cold and dry period is essentially the same as the modern era.

Ngoin Tso lies some 200 km to the east of Silling Tso and is a relatively small, brackish lake found at 4532 m.a.s.l. Jin *et al.* (2005) extracted two sediment cores from the lake and reconstructed climate based on colorimetry and the measurement of the lightness (L^*) of recovered sediments, sediment weathering measured by variation in Rb and Sr

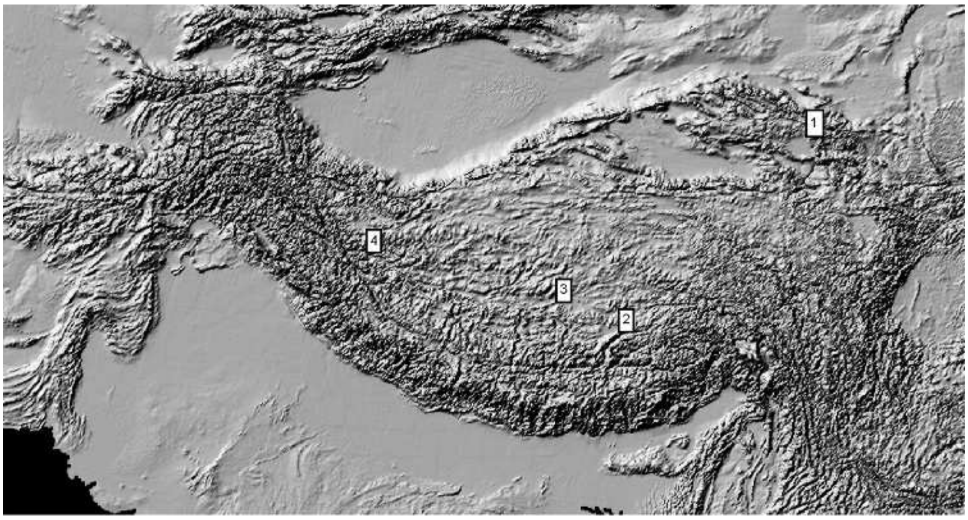

Fig. 2. Location of paleoenvironmental sampling sites. (1) Koko Nor (Lake Qinghai); (2) Ngoin Tso, Cuoe Tso, and Ahung Tso; (3) Silling Tso; (4) Sumxi-Longmu Tso.

ratios, and variability in $\delta^{13}C_{org}$. These proxies suggest an abrupt change in climate from dry-cold to wet-warm at ~12,000 Cal yr BP, with continuing warmth and wetness until ~4200 Cal yr BP. Two dry-cold periods – ~8400–8000 and ~4700 Cal yr BP – punctuate this trend. The authors suggest that these Early-to-Mid-Holocene conditions were created by a strong Indian summer monsoon. A change to cold and dry conditions is indicated starting at 4200 Cal yr BP, when the lake either dries completely or has become a shallow marsh or swamp. The onset of modern climatic conditions, not dated at Ngoin Tso, refilled the lake to its present state.

Ahung Tso is a very small, freshwater lake located at 4575 m.a.s.l. approximately 60 km northwest of Nakchu. Morrill *et al.* (2006) extracted three short sediment cores from the lake and, through an analysis of lake geochemistry, were able to define two abrupt breaks in monsoon precipitation: one between 7500 and 7000 Cal yr BP and the other around 4700 Cal yr BP. Note the abrupt break in the monsoon as monitored here corresponds well to the dry period at the same date from Ngoin Tso. Of interest is the general absence of Late Holocene lake sediments, indicating that local climate was quite dry. The lake does not begin to fill again until some time in the twentieth century.

Ngonpo Tso, a large, saline lake, is found on the extreme northeastern margin of the Tibetan Plateau at an elevation of 3194 m.a.s.l. Ji *et al.* (2005) examined a single sediment core taken from the southeastern side of the lake and analyzed pollen, carbonates, total organic carbon, and other proxies to reconstruct climate over an 18,000-year period. What makes Ngonpo Tso important for climate history is that it lies at the conjunction of three major weather systems: the Indian monsoon, the East Asian monsoon, and the prevailing westerly winter circulation. In their reconstruction, climate at 10,800 Cal yr BP was warming and becoming wetter, and the catchment of the lake was dominated by a forest steppe vegetation community, a trend that was initiated as early as ~14,000 years ago. In the period 10,800–4,500 Cal yr BP, three stages of climate were distinguished: (1) from 10,800 to 8500 Cal yr BP, climate became much warmer and wetter, with a significant expansion of arboreal vegetation communities; (2) a cooling and drying trend persisted from 8500 to 7800 Cal yr BP, with plant communities dominated by coniferous trees; and (3) the period from 7800 to 4500 Cal yr BP was characterized by two stages – a highly productive, warm and wet period from 7800 to 6500 Cal yr BP, which was marked by yet another expansion of mixed coniferous and deciduous forest and a deterioration characterized by decreasing rainfall from 6500 to 4500 Cal yr BP, when forest steppe returned to dominate catchment vegetation. This trend accelerated after 4500 Cal yr BP, transforming the region from cool and humid to arid and cold in modern times.

In summary, despite some local variation, paleoclimatic reconstructions across the plateau are reasonably consistent. Conditions during the Early-to-Mid-Holocene across the plateau were consistently warm and wet when compared to both the preceding glacial epoch and the Late Holocene. Although each region studied shows reversals to cooler and drier conditions around 8200 Cal yr BP of varying duration, wet and warm conditions were the norm after ~7500 to ~6000 Cal yr BP, although, as the data from Ahung Tso show, also characterized by abrupt changes in monsoon intensity. At least in western and central Tibet, this has been attributed to the presence of an intense Indian monsoon. Although explanations vary, it is believed that the onset of cooler and less humid conditions after 6000 Cal yr BP is consistent with a weakening of the monsoon (Morrill *et al.*, 2006). The period 4000–3000 Cal yr BP is across the plateau a time of peak aridity, with many lake levels dropping substantially. This appears to correspond to the millennial-scale Bond events (also known as Holocene Event 3; Bond *et al.*, 1997). Depending on location, modern conditions of cold and aridity were established between 2500 and 1400 Cal yr BP.

Because of the paucity of archeological data from 10,000 to 5000 Cal yr BP, it is impossible to discuss with certainty how climate variability may have affected cultural evolution on the plateau. It is possible, however, to offer a number of informed speculations that might help place the advent of the Neolithic into an environmental context.

Assuming foragers were present on the central plateau at least by 10,000 Cal BP, the amelioration of climate after this date most probably led to increased population growth, which would most likely have been greatest in the major river valleys in central Tibet, such as the Yarlung Tsangpo, in the valleys of southeastern Tibet, and in the Ngonpo Tso region of northeastern Tibet. Given the lack of data, however, it is impossible to demonstrate that population growth in any of these regions led to the appearance of sedentism, which is generally seen as an important necessary condition for the appearance a classic (i.e., village agriculturalists) Neolithic lifeway. Kha rub first appears on the extreme eastern margins of the plateau ~5700 Cal yr BP, when climate was still wet and warm, as does Jiangxigou 2 near Ngonpo Tso. Kha rub, like other Neolithic sites in this region, appears to have been abandoned sometime after ~4100 Cal yr BP, which is just after the onset of cold and dry conditions as observed at Silling Tso on the central plateau. In contrast, Chugong is first occupied during the period of maximum aridity on the central plateau at ~3500 Cal yr BP.

What can be concluded is that while the role of Mid-to-Late Holocene climate on the development of the Neolithic on the plateau is unclear, once established after ~5700 Cal yr BP, Neolithic cultures spread into the central valleys of the plateau and created the foundations of more complex societies to follow after ~2500 Cal yr BP in the Yarlung Valley. In this sense, by at least early Chugong times, the "Neolithic package" of domesticated plants (but which one?; see below), yak, sheep, and pig was fully acclimatized to the rigors of a high-elevation environment. However, insofar as it is known on the plateau, this Neolithic was riverine focused. These valleys contained the best agricultural land and, more importantly, offered ready access to fresh water, which would have been scarce in many areas of the plateau as lakes dried or became brackish during the period of maximum aridity. Other possible forms of the Neolithic, as I shall discuss below, remain to be defined.

4. Current models of the Tibetan Neolithic

Not surprisingly, there are few models of how the Tibetan Neolithic came to be, and those that have been proposed are not founded upon archeological data. The excavators of Kha rub, for example, noted that while the site has similarities to sites in northwestern Sichuan, such as Lizhou (Bureau of Cultural Relics, 1985, p. 178), they conclude their evaluation of the site by suggesting that it is a representation of an indigenous Tibetan archeological culture. Indeed, other sites in the Chamdo area, such as Rngul mdv (Chin. Xiaoenda; Bureau of Cultural Relics, 1990; Hou, 1991) with its similar cultural content, reinforce this interpretation. Although its occupations are contemporary with the Majiayao, Banshan, and Machang archeological cultures on the northeastern margins of the plateau, they are significantly different from these in terms of content and clearly do not owe their origins to them. This argument presumes that there must have been an indigenous Tibetan hunting and gathering population already on the plateau that "developed into" the Neolithic culture represented by Kha rub. But this argument ignores the obvious lowland origins of the millet and pigs found at the site, both of which were domesticated much earlier.

Models of the Tibetan Neolithic are thus connected to the complex arguments about the ethnogenesis of the Tibetan people (Aldenderfer, 2003 [2006]). If Kha rub and Chugong are "authentically Tibetan," from where did these cultures ultimately originate? What was the nature of interaction between these peoples and those lowlanders who had domesticated millets and pigs? What does it mean to assert that an archeological culture is authentically Tibetan? Given the lability of ethnic assignments, there is no single or definitive answer to such a question, and from a scientific perspective, it is futile to attempt a definition of a "Tibetan" ethnicity in the deep past. If, though, some cultural developments on the plateau are thought to be of indigenous origin, then it becomes important to determine when these indigenous peoples might have arrived on the plateau and how they may have interacted with peoples from the surrounding lowlands over time. Viewed from this perspective, we can now examine different processes that model the spread and adoption of the Neolithic, including demic diffusion (population movement), trait diffusion (spread of ideas or specific cultural traits from other peoples), acculturation, persistence of indigenous populations, or some complex combination of all of these.

The majority of models of the Tibetan Neolithic, including those by Su *et al.* (2000), Ren (2000), and van Driem (1998, 2001, 2002), tend to discount the early presence of humans on the plateau, and instead argue that demic diffusion from some lowland source created the Neolithic on the plateau. The Su *et al.* model is based on the distribution of Y haplotypes in East Asia, and they argue that around 6000 Cal yr BP, proto-Tibeto-Burman speakers move from Qinghai onto the central plateau. At this time, a "Central Asian" set of haplotypes is added to these migrants. Ren's model is primarily based on paleoenvironmental data, and he sees that sometime after 6000 Cal yr BP, a "Neolithic package" moves from the east up the major river valleys onto the central plateau. The carriers of this package are apparently lowlanders moving into the high elevations of the plateau. Finally, van Driem's model is most comprehensive of the explanations for the appearance of the Neolithic on the plateau and combines archeological, DNA, and linguistic data. He postulates the existence by 11,500 BCE of an ancestral homeland of Tibeto-Burmese speakers in the middle and upper Yangtze River of Sichuan. This population served as the source of the Early Neolithic groups in both the eastern (Peiligang) and western (Dadiwan) Yellow River basin. Both areas were occupied as early as 6500 BCE, and van Driem labels them as "Northern Tibeto-Burmese" speakers. He suggests that the clearest archeological correlate of this migration is what he terms the "abrupt" replacement of local microlithic-using cultures by the Dadiwan cultivators (van Driem, 2001, p. 417). These migrants brought with them cord-marked pottery and polished stone tools, which van Driem takes as cultural and ethnic markers. The postulated linguistic divergence that created Northwestern Tibeto-Burmese (Bodic) languages is directly correlated by van Driem with the appearance of the Majiayao Neolithic in Gansu and extreme eastern Qinghai, which he dates as early as 3900 BCE. These Bodic-speaking migrants with their Neolithic package spread across the plateau after this date.

While each of these models is plausible, they contain numerous flaws (Aldenderfer and Zhang 2004, pp. 38–39). Beginning with the Su *et al.* and van Driem models, both assume that archeological cultures are direct material indicators of ethnicity and language. Seldom, if ever, does a single artifact type, burial practice, or stylistic motif unambiguously represent a set of genes or language. Moreover, the models simply assume language dispersal via migration, and as Renfrew (2000, pp. 24–26) and others have pointed out, there are other mechanisms for language dispersal that do not assume the direct, large-scale movement of people. Another problem with the models is that they rely upon selective use of inaccurate and incomplete archeological data. Remarkably, both models ignore the existence of the central Tibetan Neolithic sites. Their use of the western Machu (Huanghe, Yellow) river data is generally accurately portrayed in terms of cultural content and dating, however, and to be fair to van Driem (2001, pp. 419–20), he does assert, following Chang (1986), that one important source of plateau population is likely to be the western Drichu (Yangtze) river valleys of western Sichuan.

However, perhaps the greatest flaw of both models is the simplistic way in which migration is conceived. van Driem (2001, pp. 423–25) offers a number of motivations for Majiayao Neolithic peoples to move to the west, including ecological calamity, stress, or simply "tidings of prosperity from the west." Unfortunately for these models, their authors appear not to have looked carefully at their maps and considered the subsistence technologies of these peoples in their desire to move them about the landscape. Both models have agricultural peoples from relatively low elevations moving up to the high plateau and across the hyperarid and frigid Changtang. Only pastoralists thrive in these portions of the plateau, and it is far-fetched indeed to believe that these sedentary agriculturalists somehow moved a Neolithic "package" across the Changtang and into the far west without significant changes to that package. These models also ignore all of the problems created by hypoxic environments and their effects on human physiology. In short, both fail to think seriously of how the subsistence system of the cultures could have been transported across these inhospitable environments, and how these cultures adapted to the known rigors of life at high elevation.

Ren's (2000) (see also Ren and Beug, 2002) model relies exclusively on the reconstruction of biome and plant communities based on pollen records from numerous sampling locations across China. Ren observed the expansion of arboreal species around 8000 Cal yr BP, which coincides with the establishment of warm and wet conditions on the plateau and across lowland China. Direct evidence for this process is observed near Ngonpo Tso, and these conditions likely characterized most of the valley systems along the eastern margins of the plateau. After 6000 Cal yr BP, arboreal forest cover begins to decline throughout China; the process began earliest in the middle and lower reaches of the Machu (Yellow) River, and was initiated on the plateau just after 4000 Cal yr BP. The cause, Ren asserts, was the expansion of Neolithic peoples across China. Although Ren argues that the onset of Holocene Event 3, the return of cold and arid conditions to East Asia, was not responsible for the decline in forest cover, this assertion is difficult to justify, given the accumulated evidence of lake-level decline and drying across the plateau. Yet another problem with the model is that there are few pollen-sampling locations on the plateau, thus making extrapolation of data from the lowlands to it problematic. Finally, given the paucity of Neolithic sites on the plateau, it is difficult to see how there were enough people present to effect such a dramatic transformation of the natural environment.

None of these models considers whether indigenous peoples were present on the plateau during these migrations. However, the dating of the initial occupation of the plateau remains unfortunately muddled, and thus, dating the presence of an early indigenous population on the plateau remains uncertain. Although most Chinese archeologists believe that the plateau was occupied as early as ~30 ka BP (Aldenderfer, 2003; Aldenderfer and Zhang, 2004), the earliest secure dates are much later in time and are found on the extreme northeastern margins of the plateau near Ngonpo Tso (Brantingham *et al.*, 2003; Brantingham *et al.*, this volume; Madsen *et al.*, 2006). Five distinct occupations have been located and dated between 13 and 15,000 Cal yr BP. These dates are consistent with materials confidently, if not yet precisely, dated to the Paleolithic found in the Changtang (Brantingham, Olsen, and Schaller, 2001) as well as across the central plateau (Aldenderfer and Zhang, 2004, pp. 15–21).

Madsen *et al.* (2006) (see also Brantingham *et al.*, this volume) have presented the most comprehensive model for the initial occupation of the plateau. They propose a "three-step" process, modified from an original version presented by Brantingham *et al.* (2003), in which (1) the lower elevations (below 2000 m.a.s.l.) of the northern margins of the plateau near Ngonpo Tso were occupied no later than 25,000 Cal yr BP by highly mobile foragers, (2) a second step dating to just before and just after the Last Glacial Maximum (~25,000–14,000 Cal yr BP) during which hunter-gatherers operating from more permanent home bases along the lower elevation margins of the plateau occupied temporary, short-term, special-purpose foraging sites on the middle (3000–4000 m.a.s.l.) and upper (> 4000 m.a.s.l.) parts of the plateau, and (3) full-scale, year-round occupation of the upper regions of the plateau by early Neolithic pastoralists.

Although this model is both plausible and testable, it ignores Chusang, which is found on the central plateau ~80 km north of Lhasa, and which according to Zhang and Li (2002) was occupied ~21,000 years BP. A new dating program of the sediments using the uranium–thorium isochron method suggests that a more probable date of occupation of the site was 28 kyr (Shangde Luo, personal communication, 2006). It is thus difficult to reconcile the existence of this site with the Madsen *et al.* model. If indeed the site was only a short-term occupation by highly mobile foragers, they would have had a very long walk indeed to their Ngonpo Tso area low-elevation base camps, a one-way trip of more than 1000 km. Although some foraging peoples are known to have large logistical foraging radii, the Madsen *et al.* model ignores the physical difficulties of travel across the plateau as well as the physiological costs of this kind of mobility. Given the high costs of high-elevation mobility seen in the early Andes (Aldenderfer, 1998), it seems more plausible and parsimonious to assert that hunting and gathering peoples were in fact permanent residents on the central plateau by at least 28 ka BP and possibly earlier.

Another concern with the model is their argument that "a fully adapted occupation [of the central plateau] did not take place until the development of pastoralist societies who could bring many of the resources on which they were dependent with them to the Tibetan high country" (Madsen *et al.*, 2006), which would be presumably some after 9000 Cal yr BP. While a form of pastoralism may indeed be yet another kind of Neolithic adaptation (see below), it is unwarranted at best to assert that only after the adoption of a Neolithic package could the plateau have been permanently occupied, given the real probability that foragers were present well before the origins of the Neolithic. But the model is useful in this instance because it serves notice that other forms of the Neolithic should be modeled since the traditional approach to its definition is biased toward the development of settled village life.

5. Alternative models of the Tibetan Neolithic

Not surprisingly, none of the models that purport to explain the origins of the Tibetan Neolithic are completely successful. However, each of them offers valuable insights into what such a model (or models) might contain. At a minimum, new models should consider the following: the origins or different modes of food production, constraints on the "Neolithic package" and consideration of sources of domesticated plants, alternative routes of entry onto the plateau, and new genetic data on adaptations to life at high elevation, dietary tolerances, and population origins. These sources of data are obviously interrelated. The goal of this discussion is not so much to develop this new model of the Tibetan Neolithic but instead to offer thoughts on a more comprehensive way to conceptualize it than has heretofore been developed. Clearly, more and better empirical data from Neolithic archeological sites will be necessary to build these models and successfully test them.

5.1 Different Modes of Food Production

Yak, sheep, and goat pastoralism are fixtures upon the plateau today, and in a sense, these modes of food production can be seen as alternative forms of Neolithic adaptations. However, as archeologists working in other regions in which pastoralism is important have noted, there are a variety of modes of production that characterize it, and it becomes important to define just what is meant when the term "pastoralism" is employed. For example, in the Levant, Cribb (1991), using ethnographic examples, defines pastoralism across a continuum: sedentary agricultural villages, limited village pastoralism, village transhumance, and nomadic pastoralism. A similar model of pastoral variability has been developed in the Andes by Inamura (1986, p. 175), who identifies four concurrent modes of production: exclusive pastoralism, pastoralism with complementary cultivation, exclusive agriculture, and agriculture with complementary pastoralism. Some variant of each of these can be seen on the plateau today: nomadic (or exclusive) pastoralism on the Changtang (Goldstein and Beall, 2002), and some form of household or village-based pastoralism known in Tibetan as the *sa ma 'brog* pattern (Samuel, 1993, p. 41), wherein animals are moved seasonally to higher elevation pastures, and simply agriculturalists with animals. *Drok pa* are known today on the plateau as nomadic pastoralists, while *shing pa* are village-based agriculturalists.

Archeologically, the materials from both Kha rub and Chugong appear to reflect groups of agriculturalists with animals, although it is impossible to know if the domesticated animals at Chugong were moved to higher pastures. In contrast, the fragmentary record from Gyaritang (at 4234 m.a.s.l.) given its location above the limits of effective agriculture suggests a form of pastoralism.

But it is important to remember that these pastoral adaptations are likely to have developed along with or subsequent to the appearance of a farming Neolithic. There are few, if any, exclusively carnivorous pastoralists in the world. Although exclusive carnivores are known ethnographically and archeologically, they are hunting societies (Bunn and Stanford, 2001). The nomadic pastoralists of Phala studied by Goldstein and Beall (2002, p. 133), for example, while heavily reliant upon butter, cheese, yogurt, and meat of their animals, nevertheless obtain as much as 50% of their caloric inputs from grains obtained through trade with farming peoples. It is very probable that many of the sites, unfortunately undated for the most part, discovered by Bellezza (2001, 2002) on the northern Changtang are the remains of a pastoral adaptation as well.

5.2 Other Routes Onto the Plateau

Aside from the thinking about Kha rub, existing models of the origins of the Tibetan Neolithic have something of a "northward" bias. That is, they see the peopling of the plateau as having its origins in the north, a position consistent with considerable genetic and archeological data. However, despite the formidable barriers of the Himalayas, Karakorums, and other mountain systems, movement onto the plateau from a number of locations from the surrounding lowlands has a deep history, but one that has yet to be explored systematically. Samuel (2000), for example, has speculated on possible connections between plateau peoples and the Indus Valley civilizations. Although similarities between the two regions are more apparent than real, it should remind us that other parts of the plateau, such as the far west along the Indus and Sutlej drainages, may have been the scene of other Neolithic occupations. Certainly, in historic times, there were strong trade connections between far western Tibet, Ladahk, and regions further to the west. The antiquity of these connections is unknown. Other potential routes of entry onto the plateau used in historic times include that through Sikkim (Gangtok-Yatung-Gyantse), central Nepal (Kathmandu-Nyalam-Dingri), and the important pilgrimage route to the holy mountain Kailash (Tise) which begins in western Nepal, enters Tibet via Purang (Tib. spurang), then proceeds directly to the mountain and its associated holy lakes.

5.3 Constraints on the "Neolithic Package" and Other Sources of Domesticated Plants

The importance of these alternative routes onto the plateau for the study of the Neolithic is that they may hold clues to the timing of the appearance of early cultigens and other domesticates as well as other aspects of material culture. Archeologically, two plant cultigens are known from the Tibetan Plateau: foxtail millet (*Setaria italica*) from Kha rub (Bureau of Cultural Relics, 1985: 168) and the so-called naked barley (*Hordeum vulgare* L. Var nudum; Fu *et al.*, 2000) from Phrang mgo (Chin. Changguogou). However, millet is not grown commonly on the plateau today, and barley has become the subsistence staple for village agriculturalists. When did barley become the staple crop, and what was its origin? Why did millet appear to drop out of the subsistence mix? Although we have few data useful in answering these questions, a consideration of the nature of the plants and their possible sources of origin can help identify possible constraints on the movement of cultigens across the plateau and, further, may help to understand how and when alternative routes onto the plateau may have been utilized.

Foxtail millet is first known from the Peiligang archeological culture (~6300–5100 BCE) of the eastern Yellow River drainage (Underhill, 1997: Table II), and as noted above, it is present in the Gansu and Qinhgai Neolithic cultures beginning with the Yangshao (ca. 5000–3400 BCE). What evidence exists suggests that what is known as the Far Eastern variant was likely domesticated somewhere in north China within its natural distribution (de Wet, 1989: 26–27), but other locations remain possibilities. Foxtail millet is well adapted to dry and warm conditions, but does poorly when soils are too heavy, rich in clay, or too wet. It has a fairly short growing season and is prone to frost damage. Although most agronomists suggest that its altitudinal limit is ca. 2000 m.a.s.l., it is grown today at elevations in the Himalayas up to 3500 m.a.s.l. (Malm and Rachie, 1971). However, it is important to note that success in its cultivation at this elevation depends on very favorable conditions and microclimates. On the plateau, the major central valley systems lie at an average elevation of ca. 3650 m.a.s.l., which slightly exceeds this altitudinal maximum. The growing season on the plateau is short, and rainfall from the Indian summer monsoon can be very intense. Given these factors, it seems that while millet can be grown in the central valleys of the plateau, it does not thrive. Millet in the past may have been confined to the eastern margins of the plateau, where it may have arrived from low-elevation sources in Sichuan.

An alternative hypothesis is that millet could have arrived from the north by demic diffusion from sources in Qinghai, a position consistent with the Madsen *et al.* (2006) and Brantingham *et al.* (this volume) argument. Although their Neolithic package has not been described in detail, it includes domestic animals as well as plants, presumably millets, since barley does not appear in China until much later in prehistory. While possible, I find the argument implausible. Most of the 600 km (in linear distance) between the Qinghai Neolithic sites and Kha rub as well as the 1000 km to the Yarlung Tsangpo valley lies at elevations well over 4000 m, which is well beyond the altitudinal limits of successful millet cultivation (Fig. 3). Given the difficulties of the environment, it seems unlikely that millet could have been moved across it, then planted, by groups of people reliant upon it for their subsistence.

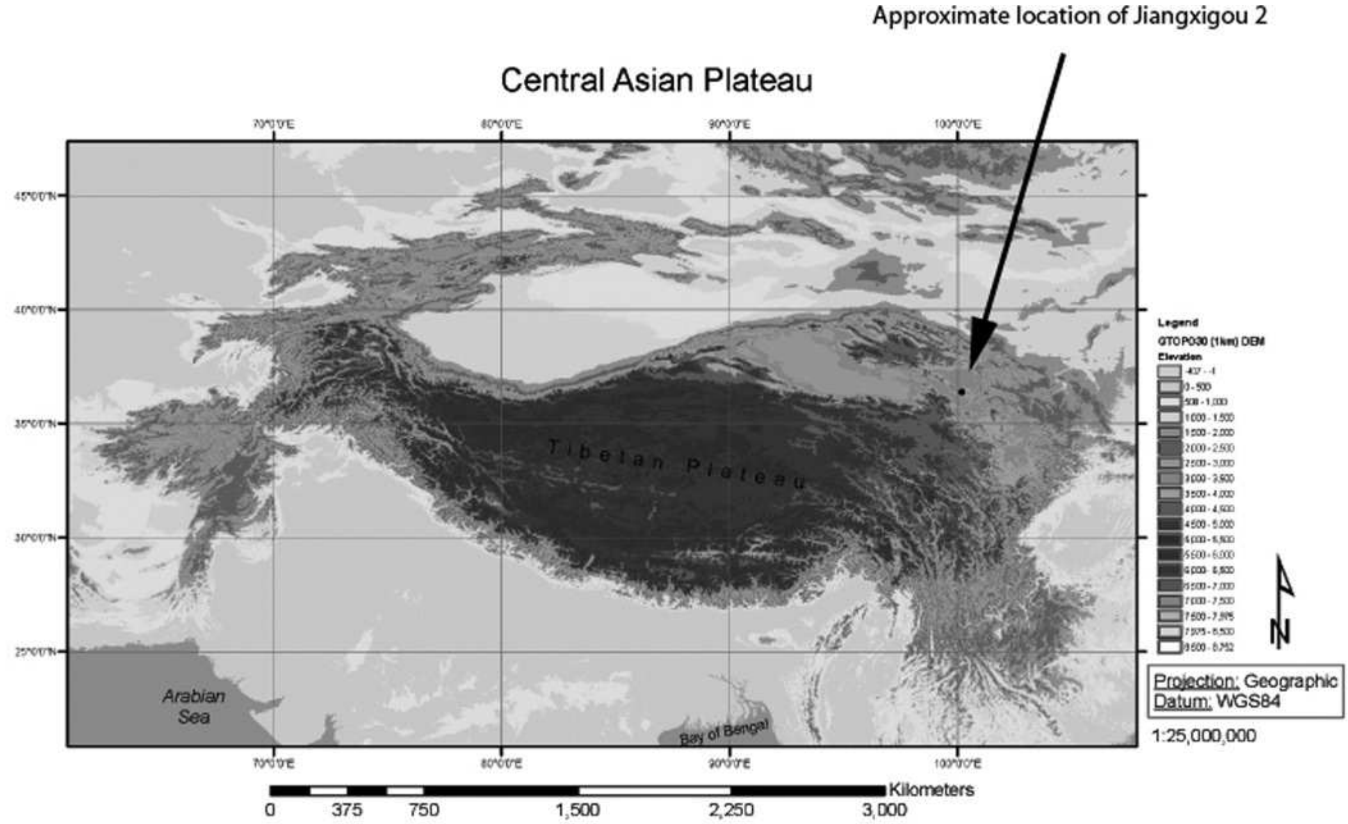

Fig. 3. Elevation map of the Tibetan Plateau and surrounding regions. Contours are at 500 m intervals. Map based on GTOPO30 1 km data. Map courtesy of Nathan Craig.

How barley (*H. vulgare* L. Var nudum) became a fixture of Tibetan subsistence practice is somewhat more difficult to untangle. Domesticated barley is well known from the Neolithic of the Middle East, more specifically the Fertile Crescent, and until recently, the region was assumed to be the single center of its origin some 9000 years ago (Molina-Cano *et al.*, 2002: 18–23). Barley was assumed to spread both east and west via seed exchange (von Bothmer *et al.*, 2003: 15–6) and, under this model, did not arrive in western and northern China until ~1000 BCE. What threw this neat model into confusion was the discovery on the plateau in the 1980s of one of the wild progenitors of barley – *Hordeum spontaneum* (Molina-Cano *et al.*, 2002: 18). This, combined with the existence on the plateau of a non-brittle, so-called naked (domesticated) rachis form of *H. vulgare* that has a different genotype from the barleys of the Middle East and India, fueled speculation among Chinese scientists that Tibet witnessed an indigenous domestication of barley perhaps as early as 5000 years ago (Xu, 2002; Ma *et al.*, 1987). Furthermore, other aspects of the genetic diversity of this Tibetan barley, specifically the lack of an "undifferentiated geographic pattern," suggest a relatively recent radiation from a domestication center (Molina-Cano *et al.*, 2002: 18). While far from resolved and rather controversial, Molina-Cano *et al.* (2002: 25) believe that the evidence is strong enough to name Tibet as a secondary center of barley domestication.

This claim has gained considerable support by the discovery of carbonized barley kernels from Phrang mgo (Fu *et al.*, 2000), which is dated to 1370 BCE (He, 1994; Institute of Archaeology 1999b). Although not recognized in the initial excavation of the site, these kernels were recovered from a large pit feature by a team of plant scientists recording wild stands of barley on the plateau (Fu *et al.*, 2000). Interestingly, the date of occupation of the site overlaps with that of Chugong, which is not known to contain evidence of early barley use.

The problem, of course, is that there is no anthropological context within which to embed this hypothesis. If people did not live in the central Tibetan Plateau until the Neolithic and arrived from a northerly source, did these migrants simultaneously move onto the plateau and initiate a domestication process with the wild barleys present? Or was there an indigenous population of foragers already present on the plateau who initiated the process? Did these peoples create at least one part of their own Neolithic package? But given the data we have at present, it appears that barely as it is known on the plateau did not come from either India or northern Nepal since the genetic structure of the barleys between these regions is different (von Bothmer *et al.*, 2003: 16–17). Until more Neolithic sites are discovered, however, these ideas remain little more than fascinating speculations.

The constraints on the animals of the Neolithic package bear some discussion. As Flad *et al.* (this volume) note, aside from the yak, all domestic animals in northwestern China, including the Tibetan Plateau, are thought to have been domesticated elsewhere. This means that each animal species – pig, goat, sheep, cattle, donkey, and horse – evolved as lowlanders and thus had to acclimatize to life at high elevation. These species would have suffered the same reproductive constraints as did humans until they became fully acclimatized to life at high elevation. However, pig (litter size range of 6–12) and goat (1–3) would have been able to adjust relatively rapidly because of their tendency for multiple births, which would have afforded them the probability of a greater proportion of live births surviving the initial drop in fertility as the acclimatization process is initiated compared to those species with long gestation periods and single offspring, such as cattle, donkey, sheep, and horse. It would have taken these species somewhat longer for their populations to grow at high elevation. However, if humans only harvested secondary products such as milk and wool from cattle and sheep instead of meat, this constraint would have been somewhat lessened. But if meat was the primary consideration for the use of these domestic animals, growth in herd size may have been slowed considerably.

5.4 Dietary Preferences and Adaptations to High Elevation

A key feature of a nomadic (or exclusive) pastoral adaptation is the heavy use of dairy products, which in the Tibetan case includes butter, cheese, yogurt, and, to a lesser extent, milk. These products are made from the three animal domesticates – the yak, goats, and sheep. As noted above, these products comprise at least 50% of the diets of modern Tibetan pastoralists. In contrast, East Asian peoples, who may possess domesticated animals, do not consume dairy products of any kind. This difference in dietary preference is reflected in many instances in the genes of these peoples. As Holden and Mace (2002) have shown, there is a clear correlation between pastoralism, especially the consumption of milk, and high levels of lactase persistence. Milk and its byproducts contain lactose, or "milk sugar," and the ability to digest lactose declines sharply over the lifetime of a person. The ability to digest it into adulthood is termed lactase persistence, and Holden and Mace (2002, p. 280) note that it "is associated with a single-locus genetic polymorphism," which is inherited as a dominant trait. Among the questions that can be examined regarding the persistence of this trait is whether it is transmitted horizontally or vertically. "Horizontal diffusion is defined as the transmission of biocultural traits between neighboring populations," whereas "vertical inheritance is defined as transmission from 'mother' to 'daughter' populations" (Holden and Mace, 2002, p. 284). They further note that vertical transmission is primarily associated with population, or demic, diffusion.

This discussion is directly relevant to our consideration of the origins of the Tibetan Neolithic. If demic diffusion is responsible for the movement of Neolithic peoples onto the plateau, the origin of that movement may be charted by examining frequencies of lactase persistence in possible source populations. Aside from the Han, however, no studies of its frequency in relevant source populations have been undertaken. Of interest, however, is the recorded frequency of lactase persistence – 12% – in the Mongols (Holden and Mace 2002, Table 12.1). For a group so dependent on milk and its byproducts, this is remarkably low when compared to northern European pastoral peoples such as the Sámi (59%) or western Asian pastoralists such as the Bedouin (83%) or the Beja (87%). Holden and Mace suggest that despite the dominance of this trait, such a low frequency in a pastoral population implies that the group in question has turned only recently to pastoral pursuits. They further propose a coevolutionary model of milking and lactase persistence. They argue that from a condition of no milking and low levels of lactase persistence, it is probable that milking developed first and was followed by higher levels of lactase persistence. Their data indicate that lactase persistence is an adaptation to milk and dairy dependence through pastoralism (Holden and Mace, 2002, p. 298).

Both vertical and horizontal diffusion of pastoralism into Europe have been modeled, and this provides a basis for thinking about what might have taken place on the Tibetan Plateau. Holden and Mace (2002, pp. 301–302) cite a study by Bodmer and Cavalli-Sforza (1976), who show that by assuming a low initial incidence of the dominant gene (1%) and a selection coefficient of 0.015, it would take 290 generations to fix the dominant gene frequency at the level observed today in modern European populations, a time frame consistent with what is known of animal domestication in the Middle East and also consistent with the timing of models of demic diffusion of populations into Europe from that source area. Flatz (1987) modeled a process of horizontal diffusion, and assuming a very low initial frequency of the gene, a higher selection coefficient was required to get gene frequencies to approach those seen in modern northern Europe, assuming that 3500 Cal yr BP was the date of appearance of domesticated livestock. As Holden and Mace (2002, p. 302) note, however, both of these models assumed a low initial frequency of the dominant gene in contrast to their model. Regardless of the specifics of the models; however, it is clear that either form of diffusion remains a possibility to explain the origins of nomadic pastoralism on the plateau especially if we assume that an indigenous population of hunter-gatherers was present there well before 10 ka BP. Unfortunately, Tibetan populations have yet to be examined for lactase persistence, so testing these models remains to be accomplished in the future.

A related question concerns the nature of physiological adaptation to high-elevation life observed in native Tibetans when compared to other high-elevation peoples. Beall (2001, 2003) and others have shown that there are significant differences between Tibetans, natives of the Andean altiplano, and the Ethiopian plateau in terms of the physiological adaptations to hyperbaric hypoxia. Among the hypotheses developed to explain these differences are the following: longer residence at high elevation creates a distinctive set of genetic adaptations to hypoxia, different initial conditions of migrating populations to high elevation are responsible for observed differences, and finally, there is no single pan-human response to life under hypoxic conditions. At least the first two of these can be addressed by archeological data and are relevant to this discussion of the Tibetan Neolithic. The first hypothesis is consistent with archeological models that posit a longer term of residence on the plateau that goes back at least to 10 ka BP and probably earlier. This model further implies that trait diffusion, not demic diffusion, is the most probable source of the cultigens, domesticates, and other material aspects of the Tibetan Neolithic since there would not be sufficient time for distinctive genetic adaptations to develop if a demic diffusion after 6000 Cal yr BP was the origin of indigenous Tibetans and their Neolithic adaptations. Alternatively, if observed variability in adaptation to hypoxia is dependent not on length of residence at high elevation but instead on different initial genetic conditions of migrant populations, models that support demic diffusion as the source of Neolithic adaptations become more plausible. More complex models can also be envisioned under these scenarios.

6. Conclusions

Despite our lack of knowledge, these are exciting times in the study of the Tibetan Neolithic. Granted, the pace of research is frustratingly slow, and there is no guarantee that it will quicken over the next decade (Aldenderfer and Zhang, 2004, p. 49). It remains the case that many standard techniques used elsewhere in the world to examine subsistence practice in detail, such as flotation, pollen, phytolith, and faunal analysis, have yet to be employed at the archeological sites on the plateau, but there are hopeful signs that this situation is changing for the better.

But these improvements in method will only be successful if more nuanced thinking is applied to the origins and development of the Neolithic on the plateau. To date, models of the Tibetan Neolithic have been either static stage models of culture history or those that assume that demic diffusion is the only possible means by which the plateau could have been occupied. As I have shown in this paper, there are a variety of other models worthy of consideration that do not make this critical limiting assumption. Given what we know of plateau prehistory, it is reasonable to assume there were indigenous peoples on the plateau before the appearance of the Neolithic, and the question then becomes one of untangling various scenarios of culture process, the transmission and diffusion of material culture and cultigens, and a more hard-headed look at just where and when demic diffusion was a part of this process. It is very likely that given the size of the plateau and the number of potential routes to it, explanations of the Tibetan Neolithic will take on a mosaic character, and no single explanation of its origins is very probable.

These more nuanced models, however, must be fully multidisciplinary in their scope. This is a lesson learned in every region of the world in which there has been significant progress made in understanding Neolithic origins. These anthropologically oriented models must include detailed paleoenvironmental reconstructions, and happily, this is one of the success stories of research on the plateau. Because the Tibetan Plateau is an integral part of modern climate models, it has been the scene of significant paleoenvironmental research over the past 20 years, and given recent concerns with global warming, even more research will be undertaken over the next decade. This will significantly expand our understanding of Late Pleistocene and Holocene climate dynamics.

These models must also include consideration of the physiological constraints of life at high elevation and their effects on settlement mobility and population growth. Every model developed to date simply ignores the realities of hypoxia and cold stress, which combine to create a unique adaptive challenge for humans and, of course, for their domesticated animals. Research from other high-elevation regions has shown that until fully acclimatized to life at altitude, foragers practiced modified forms of logistical mobility that tended to minimize moves across the landscape (Aldenderfer, 1998, 2003). This would have affected the earliest migrants to the plateau as well as any other demic diffusions to it associated with the Neolithic. Importantly, until full acclimatization takes place, population growth at elevation is slow until female reproductive physiology is transformed to cope with hypoxia. This implies that models of demic diffusion onto and across the plateau, for example, would have to consider substantially lower rates of population growth when determining the budding of "daughter" communities from parent villages. Note that this problem would also affect any animal populations brought with these peoples.

Finally, new models of the Tibetan Neolithic must incorporate what is known of the genetic relationships of the peoples on the plateau, the likely sources of their origin, and emerging data on the establishment of genetic adaptations to life at altitude. This will necessarily involve more, and more comprehensive, analyses of the Tibetan genome. Models based on mitochondrial or Y haplotype DNA have identified in modern Tibetans a "central Asian" influence, and this has driven much of the discussion of the origins of the earliest inhabitants of the plateau. If these migrations were early enough, at least one model for the genesis of genetic adaptations to high-elevation life – a long length of residence at altitude – would be partially satisfied. However, if other demic diffusions have occurred, they have yet to be consistently identified in modern Tibetans, and further, if such models are correct, this suggests that length of time at altitude is not a prerequisite for the genesis for the observed Tibetan physiological defense to hypoxia. What this means is that archeologists will have to take into account these studies and see how they fit with their own reconstructions of the Tibetan past, and not simply ignore them.

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11

Zooarcheological evidence for animal domestication in northwest China

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Abstract

The history of prehistoric domesticated animal exploitation in the northwestern areas of modern China is complex and involves different processes for each of the various animals that have been documented. This chapter comprehensively summarizes the zooarchaeological evidence for animal domestication in this region and summarizes our current understanding of dog, pig, cattle, water buffalo, yak, sheep/goat, camel, donkey, and horse exploitation.

1. Introduction

In various areas of the world, the origins of animal domestication have remained a persistent focus of archeological research because the creation of symbiotic relationships between humans and animals affected both in fundamental ways. The domestication of certain animals improved the ability of humans to mitigate periods of environmental stress, allowed for progress in certain types of production activity including both hunting and agriculture, made secondary products such as milk, traction, hair, eggs, and offspring, and primary products like bone, tendons, hides, and meat more readily available, enabled longer distance over-land transport of bulky commodities, and provided companionship; but the conditions of domestication also increased the frequency of animal-borne diseases, reduced the variability and nutritional content of some peoples' diets, and, like the adoption of agriculture, encouraged the development of property rights while exacerbating and reifying social inequalities based on gender and other difference (Diamond 1987).

Domestication can be defined as "that process by which a population of animals becomes adapted to man and to the captive environment by some combination of genetic changes occurring over generations and environmentally induced developmental events recurring during each generation" (Price 2002: 11). Phenotypic change is caused by this process and in particular by the "complex interplay of organic, organismic, and environmental factors during ontogeny" (Price 2002: 11), as domesticated animals adapt to the human-created environment in which they are raised. This definition recognizes that the specific conditions of captivity and animal-human interaction may be quite varied, and these specific conditions may affect the phenotype of animals in various ways, at different rates, and to greater or lesser degrees. But the definition also stresses the effects of changes in the adaptive environment that would affect the phenotype of a domesticated animal and which, in many cases, would be visible archeologically. Nevertheless, because domestication is multifaceted, the degree of phenotypic change can vary a great deal.

Because domestication has several important facets, it is important to realize that no single line of archeological evidence can be relied upon as the only means of identifying either the process of domestication or the presence of domesticated animals in archeological contexts, and this is particularly true of the initial stages of a domestication process. Although a thorough discussion of these issues is not within the scope of this paper, it is worth enumerating some of the lines of evidence commonly used in archeological investigations of domestication. First, physiological traits are a commonly used clue. It is well known that many animals became smaller as populations were domesticated, and the conditions of domestication also affected other aspects of skeletal morphology. Measurements on animal teeth from a collection are a reasonably good proxy and other characteristics, such as crowding in tooth rows, are also indicators of domestication of animals such as pigs and dogs. Other bones can be used to investigate size in a faunal population as well. A recent study comparing bovine bones from Neolithic sites in North China, for example, shows how wild and domesticated specimens may be distinguished based on metric analyses (Tang *et al.* 2003).

Second, the age profiles of skeletal populations are also commonly used evidence. Collections that include high overrepresentations of animals of certain ages indicate selective culling of animal populations that reflect domesticated animal use. Third, disproportionate numbers of male and female animals likewise may reflect intentional culling patterns related to domestication. Fourth, although not necessarily reflecting the effects of domestication per se, high percentages in faunal assemblages of bones from certain types of animals that are known to have become domesticated at some point are often used by archeologists as an indication of developing domestication. Initial dependence on certain taxa may precede morphological changes in populations and therefore be reflected only in the composition of a site's faunal assemblage. Fifth, in some cases, the archeological contexts in which animal bones are found reflect a degree

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of human-animal symbiosis. When animals are frequently and regularly included in human burial practices, for example, this may reflect the symbolic and economic importance of such animals and, perhaps, property ownership. Sixth, isotope analyses of animal bones are a developing line of inquiry that may reflect changes in animals' diets related to the development of animal domestication.

Finally, DNA analyses are also a potentially fruitful means of investigating animal domestication. Previous studies have explored the genetic diversity of modern populations in order to understand the antiquity of changes related to domestication (Jansen *et al.* 2002; Larson *et al.* 2005; Leonard *et al.* 2002; Troy *et al.* 2001; Vilà *et al.* 1997, to name a few). Studies using ancient DNA are also underway and have the potential to further clarify genetic relationships and divergences, despite the very real difficulties of dealing with fragmentary ancient DNA.

These different lines of evidence related to the domestication process do not all reflect identical changes in the relationship between animals and humans, or the relationships of domesticated animals to wild ones. Comparison of DNA evidence, for example, reflects the genetic changes that result from particular selective conditions, which, in the case of domestication, are often imposed by the specifics of animal exploitation by humans. In fact, as mentioned above, it is the emergence of symbiotic conditions that create such permanent changes that defines true domestication. Morphological changes such as size diminution and tooth crowding are phenotypic results of this same general process. Other evidence of close human/animal interaction, such as large scale use of a particular animal species, the use of animals for rituals including osteomancy and burial practice, artistic rendering of specific animal taxa, and evidence of the use of secondary products of animals (including hair, milk, and dung), may or may not reflect domestication per se. In some archeological contexts, such data are all we have to infer that domesticated animals are being used. For the purposes of the current overview, we focus primarily on the zooarcheological evidence of animal exploitation from excavated, prehistoric sites in Northwest China. A complete discussion of iconographic, genetic, ritual, and indirect evidence of animal domestication is beyond its scope, although occasionally we introduce some such evidence, and Rhode and Madsen discuss other data elsewhere in this volume.

Until recently, archeologists working in mainland East Asia have failed to systematically collect or analyze faunal data in a way that would allow for the rigorous examination of these various lines of evidence for domestication, despite China's accepted position as a "center" of agricultural origins and an equally important locale of indigenous animal domestication. In general, with a few exceptions (Olsen 1984; Olsen *et al.* 1980; Yuan Jing 2002; Yuan *et al.* 2002; Yuan and Flad 2002; Zhou and Grigson 1984), the domestication of plants and animals in China has been underrepresented in literature on the subject (Shelach 2000: 366). Progress in our understanding of the development of rice agriculture has been made due to a recent flurry of information on early cultigens in southern China from open-air sites such as Bashidang 八十壋[1] and Pengtoushan 彭頭山, from caves at Xianrendong 仙人洞, Yuchanyan 玉蟾岩, and Diaotonghuan 吊桶環 (Chen 1999; Cohen 2002; Crawford and Shen 1998; Higham and Lu 1998; Huang and Zhang 2000; MacNeish and Libby 1995; Pei 1998; Sato 2002; Yan 1997, 2002; Yasuda 2002; Yuan Jiarong 2002; Zhao Zhijun 1998), and from waterlogged sites such as Hemudu 河姆渡 and Kuahuqiao 跨湖橋 (Guojia Wenwuju 2003; Zhang Wenxu 2000; Zhang and Tang 1996; Zhao and Wu 1989; ZSWKY 2003; ZSWKY and XB 2004) where preservation conditions are relatively good. Although relatively less clear, our understanding of the process by which cereal agriculture emerged in *North* China has improved due to recent research identifying incipient agriculture subsistence strategies in China's Northeast (Shelach 2000; Zhao 2003), and due to the efforts to understand the origins of agricultural lifeways in areas to the northwest of China's Central Plains, as demonstrated by some of the chapters in this volume.

As our understanding of agricultural origins improves, it might be expected that the information concerning animal domestication would as well. This has been true, in fact, in certain exceptional cases. For example, the previously mentioned site of Kuahuqiao (ca. 8.2–7.0 ka[2]), recently excavated in Xiaoshan 蕭山, Zhejiang 浙江 Province has allowed us to push back some of the patterns of resource exploitation seen at Hemudu (ca. 7.0–5.2 ka) even further (ZSWKY and XB 2004). Not only have rice remains strengthened the possibility that early rice agriculture was adopted in this coastal area, but pig bones from the site have been demonstrated to be the earliest evidence of domesticated swine in southern China (Yuan and Yang 2004). The primary evidence for pig domestication at this site is tooth crowding and the small size of the M3 molars of the pig specimens. In the case, therefore, the earliest currently available evidence for animal and plant domestication on the southeast coast are rather contemporaneous – although future research may yet show this to be an artifact of preservation.

Elsewhere in China, however, this contemporaneity does not seem to hold. Several sites roughly contemporary to Kuahuqiao suggest that pig domestication began in several places in China around 8000 years ago. Among these, the best-known example is the site of Cishan 磁山, a site located in Wu'an 武安 County, Hebei 河北 Province and dating approximately 8000 Cal yr BP (Yuan and Flad 2002). By this time, millet agriculture was already well established in the region (HSWG and HSWB 1981; Zhou 1981, compare Barton *et al.*, in this volume). During the Peiligang 裴李崗 period (ca. 9.5–8.0 ka), domesticated pigs in North China are found in contexts with abundant millet remains at sites

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[1] The location of all sites mentioned in the text can be found on Fig. 1.

[2] With the exception of historically known ages, which are listed as AD/BC dates, all general date ranges referred to in this discussion are listed as calendar years before present (Cal yr BP) based on calibrated radiocarbon, unless otherwise specified. Some of the spans are more well-established than others, but a thorough discussion of the issues concerning dates in the Chinese Neolithic and Bronze Ages is beyond the scope of this paper.

such as Jiahu 賈湖, where rice remains have been found well outside the range of the wild grain (Sato 2002; Yasuda 2002). Rice in this region was either newly introduced from the south around this time, or its cultivation in the region began even earlier (Chen *et al.* 1995; Cohen 2002; Yan 1997; Zhang and Wang 1998; but see Crawford and Shen 1998). Although some scholars have previously identified pig remains from sites such as Zengpiyan 甑皮岩 (located in Guilin 桂林, Guangxi 廣西, with radiocarbon dates said to be 10000 years old) as earlier evidence of domestication (Nelson 1998; Liu *et al.* 2001: 4), the support for this position is not strong (Yuan and Flad 2002: 724–725). Present evidence does not yet allow us to push back pig domestication earlier than the Cishan period – although by that point, the Cishan pigs had already undergone morphological changes.

The adoption of other domesticated animals was even further removed from agricultural origins. In central parts of China, cattle and sheep do not seem to have been domesticated until less than 6000 years ago, and water buffalo may have been adopted in southern China even later (Liu 2004a; Liu *et al* 2004a, 2004b, Yang and Liu 2004). Similarly, horses are not added to the domesticate complex in central China until the mid-second millennium (Yuan and Flad 2005; Linduff 2003; Mair 2003). For many of these animals, such as the horse, the current data probably provides a pretty good picture of the general picture of the period when domesticates entered China – although further data will improve our understanding of the routes, timing, and processes by which domesticated horses entered China from the Northern and Central Asian steppe. In other cases, however, our interpretations are severely hampered by inconsistent faunal collection techniques and by the shortage of qualified zooarcheologists to engage in rigorous studies of the remains from Early to Middle Holocene sites. The northwest is one region where our interpretations currently rely on very spotty information. Nevertheless, it is worth our time to examine the data from this region in order to further clarify the overall picture of animal domestication in various regions of China. We review here the corpus of published material and where possible, specify the reasons why certain taxa have been identified as domesticated at the sites discussed (Fig. 1). We hope that this provides a starting point for more rigorous investigation of the process and timing by which the various relevant taxa were domesticated in the region.

2. Hexi Corridor

For the purposes of this discussion we concentrate on the Hexi 河西 Corridor and surrounding regions in order to construct a preliminary sketch of the current state of zooarcheological data in this general area. After initially discussing the Hexi region itself we work outward into adjacent areas. First we consider the Upper Yellow River Valley in southeastern Gansu 甘肅 and eastern Qinghai 青海 immediately to the southeast. We then move east to the Wei 渭 River Valley in Gansu and western Shaanxi 陝西 and Arid North China – i.e., the arid regions to the north and east of the Longshou 龍首 Mountains in southwestern and south-central Inner Mongolia including the Ordos region and the Ningxia 寧夏 Autonomous Region. Finally we consider regions to the south and southwest of the Hexi Corridor in highland Tibet and Xinjiang 新疆 to the west. This breakdown is based essentially on physiographic zones within which there is a degree of consistency in the material culture. These physiographic zones do not always neatly correspond to the geographical extents of archeological cultures, however. Nevertheless, they remain useful heuristic tools for organizing our data.

When the scattered data are brought together, a general picture begins to emerge. However, it is important to note that the *published* faunal data from these regions are extremely scarce, and so we can only present a very preliminary outline of zooarcheological data related to early domesticated animal use in these regions. Furthermore, these data are not necessarily representative of the corpus of faunal remains excavated and examined so far in this part of China. Recently, Chinese zooarcheologists and their students have been responsible for a surge of new research on Holocene faunal assemblages. As more data are published over the next several years, the picture we have of the beginnings of use of various domesticated animals may become increasingly clear. Hopefully, as these data are published, their details will allow for a more nuanced picture of the evidence for the presence of domesticated animals of various taxa in the northwestern parts of China.

The Hexi Corridor lies between the Qilian 祁連 Mountains to the south and the Longshou Mountains to the north and comprises a valley of alluvial fans deposited by landlocked rivers that run northward off of the Qilian range (Fig. 2). This corridor stretches from the Dunhuang 敦煌 region on the northwest to the Tianzhu 天祝 area on the southeast and contains relatively fertile land that has sustained communities for millennia (Fig. 3). In this region, despite its prominent position in the archeology of later periods – particularly during the post-Han period when the Silk Road became a major route of communication – the amount of archeology that has been focused on early remains is quite minimal.

The basic Neolithic cultural sequence for the region begins with later part of the Yangshao 仰韶 period (ca. 7.0–5.0 ka), although the early cultural phases in the Hexi area are not well understood prior to the Shilingxia 石嶺下 (ca. 5.6–5.2 ka) and the Majiayao 馬家窯 (ca. 5.2–4.7 ka). Majiayao sites are distributed in the upper reaches of the Yellow River valley from Qinghai 青海 into Gansu and western Shaanxi and into the Hexi Corridor river valleys as far west as Jiuquan 酒泉 City in Gansu and Tongde 同德 County in Qinghai, and as far south as the upper Minjiang 岷江 and Dadu He 大渡河 river systems in northwest Sichuan (Li 2003: 25; 2005: 240). Most characteristic of this culture is painted pottery with geometric and animal designs rendered in black paint on a red or yellow background. Bone and polished stone tools are common and residential features include rectangular, semi-subterranean houses. Banshan 半山 (4.8–4.3 ka) and Machang 馬廠 (4.3–4.0 ka)

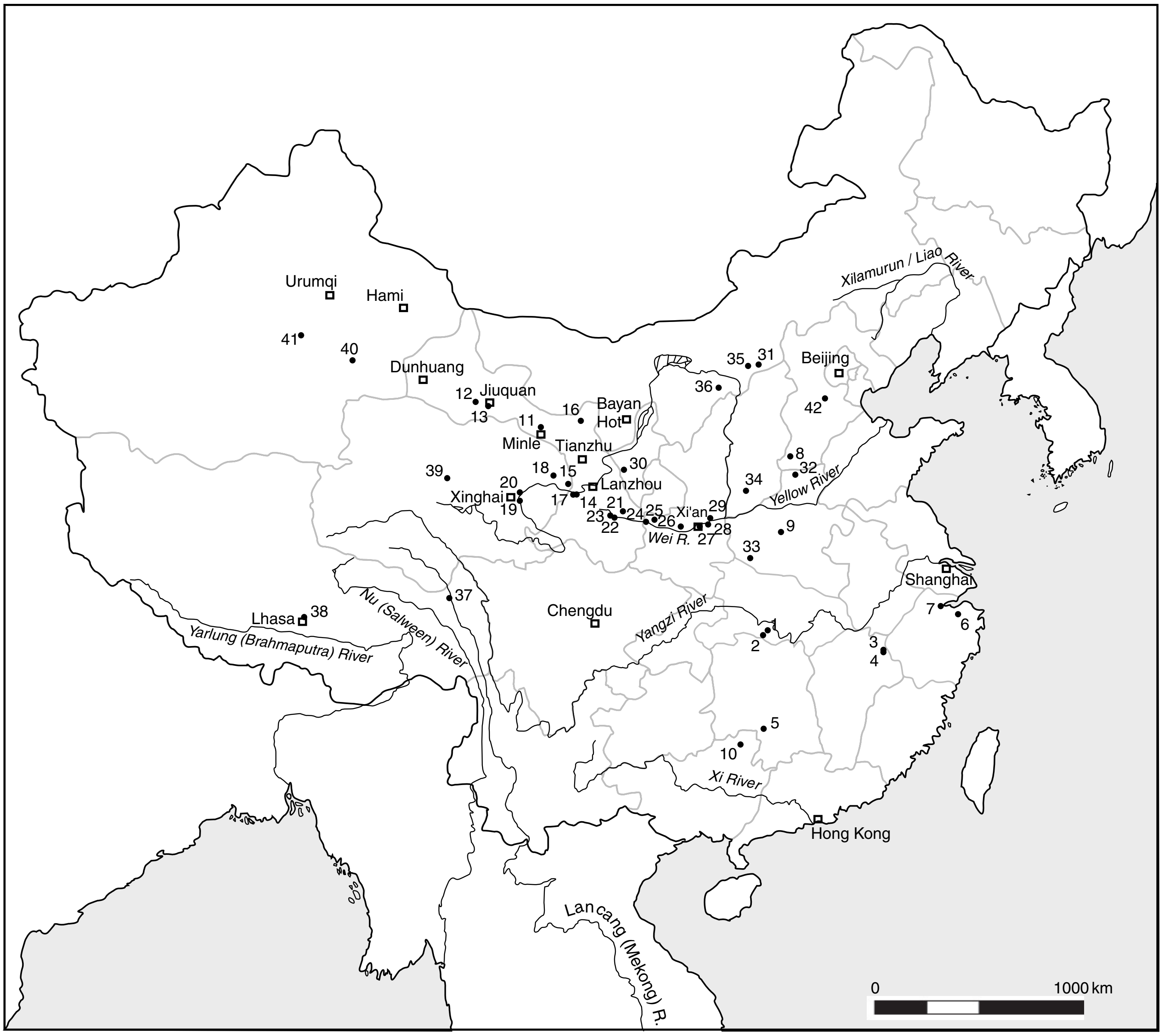

Fig. 1. Sites mentioned in the text. 1. Bashidang; 2. Pengtoushan; 3. Xianrendong; 4. Diaotonghuan; 5. Yuchanyan; 6. Hemudu; 7. Kuahuqiao; 8. Cishan; 9. Jiahu; 10. Zengpiyan; 11. Donghuishan; 12. Huoshaogou; 13. Gan'guyan; 14. Zhangjiazui; 15. Hetaozhuang; 16. Xigang, Chaiwan'gang, and Hamadun; 17. Dahezhuang and Qinweijia; 18. Liuwan; 19. Zhongri; 20. Yangqu Ershidang and Xiangnagou; 21. Dadiwan; 22. Shizhaocun; 23. Xishanping; 24. Beishouling; 25. Fulinbao; 26. Anban; 27. Banpo; 28. Jiangzhai and Linkoucun; 29. Baijiacun and Kangjia; 30. Linziliang and Mayingziliang; 31. Miaozigou and Dabagou; 32. Yinxu; 33. Xiawanggang; 34. Qucun; 35. Daihai region sites; 36. Zhukaigou; 37. Karuo and Changguogou; 38. Qugong; 39. Dalitaliha; 40. Qawrighul and Xiaohe; 41. Chawuhu Goukou; 42. Nanzhuangtou.

archeological remains developed out of the earlier Majiayao material culture and are distributed in the same general areas – although Banshan and Machang sites are not found as far to the south or east and their distribution includes areas further to the northwest in the Hami 哈密 area of eastern Xinjiang. Semi-subterranean dwellings and burials with painted pottery vessels and wooden coffins are characteristic of these cultures. They are differentiated primarily based on pottery forms and decorations.

The subsequent Qijia 齊家 Culture (ca. 4.2–3.8 ka) covers an extensive area centered slightly to the east of these previous units (see Debaine-Francfort 1995; Fitzgerald-Huber 1995, 2003; Li Shuicheng 2005; Mei 2003; and Xia Nai 1946 for Western language discussions of Qijia remains). Its western extent is in the Yongchang 永昌 County area in the Hexi Corridor and the Tongde County area in Qinghai. To the north, Qijia Culture sites are found around Alxa Left Banner (a.k.a. A'lashan Zuo Qi 阿拉善左旗 and

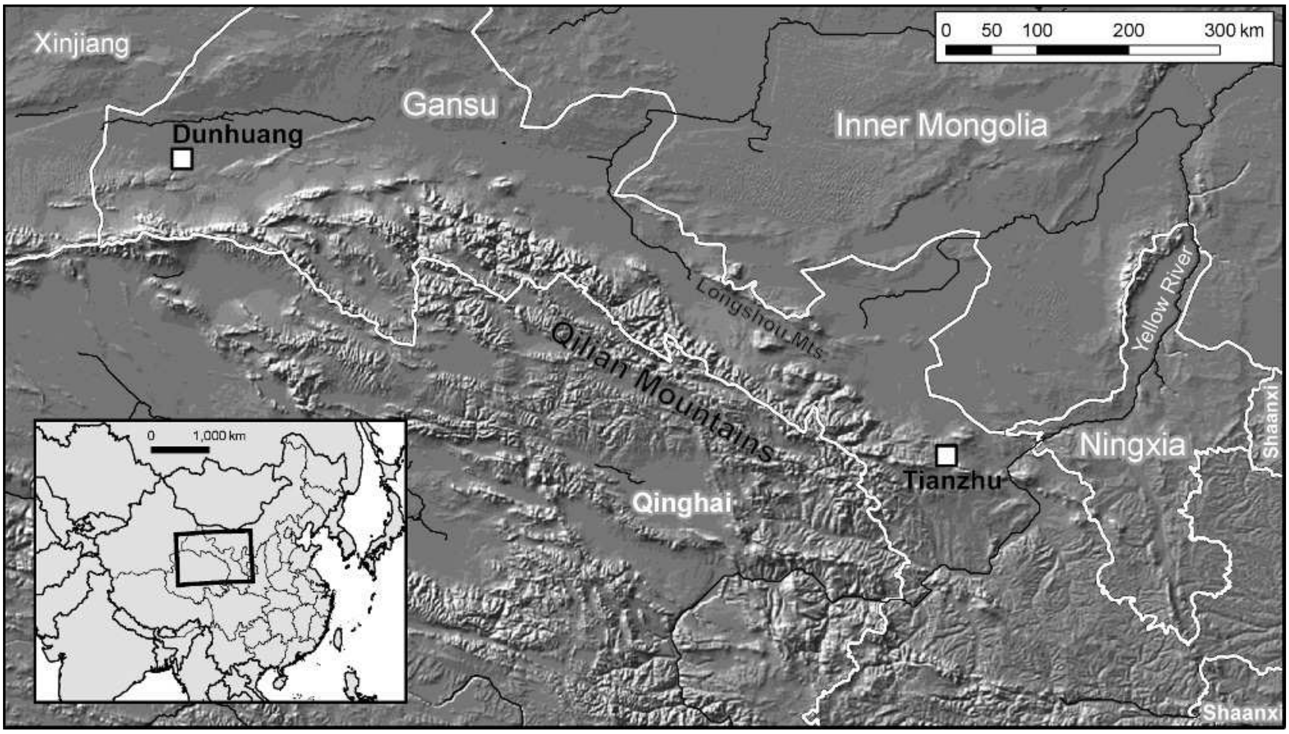

Fig. 2. The topography of the Hexi Corridor in "hill-shade" relief. The corridor stretches from Dunhuang to Tianzhu between the Longshou and Qilian Mountains in Gansu Province.

Fig. 3. Landscape near Donghuishan in Minle County, Gansu. (Photo by Rowan Flad.)

Bayan Hot 巴彦浩特) in Inner Mongolia (Qi 1962). This culture is one of the earliest whose material remains includes significant numbers of bronze objects, which demonstrate that Qijia people played an important role in the development of bronze production traditions in East Asia (Li Shuicheng 2005). The material culture found at Qijia sites, particularly the various bronze objects, reflect a complex process of transregional contact between the upper Yellow River valley and Central Asian areas during this time (Fitzgerald-Huber 1995, 2003; Mei 2003). Following the Qijia Culture, sites in the Hexi Corridor from as far west as the Hami area in Xinjiang to the upper Yellow River in the southeast are affiliated with the Siba 四壩 culture (ca. 3.9–3.5 ka) (Li and Shui 2000; Yang Jidong 1998). Subsequent archeological cultures include the Siwa 寺窪/Kayue 卡約 culture (ca. 3.3–3.0 ka), and the Shanma 騸馬, Xindian 辛店, and Shajing 沙井 cultures, the former two dating to around 3.0 ka and the latter dating to the period from the Western Zhou to the Springs and Autumns period (Li Shuicheng 2001, 2002, 2003, 2005a).

2.1 Donghuishan 東灰山

Despite the existence of sufficient data to construct such a cultural chronology for this region, faunal remains from early sites are completely unpublished. Even Qijia sites, which have been discussed extensively, do not provide published data from within the Hexi area. Donghuishan is the earliest site with reported archeofauna. This important site, located in Minle 民樂 County, Gansu, was initially examined in 1958 and again in 1978, and then more thoroughly investigated in five seasons between 1985 and 1989 (GSWKY 1995; GSWKY and JDBKY 1998; Li and Mo 2004; Ning 1960). The cultural remains from the site are all associated with the Siba Culture (ca. 3.9–3.5 ka) (Li and Shui 2000; Yang Jidong 1998). Although most of the excavation at the site concentrated on a small cluster of burials, part of the residential area was also investigated. The site report provides a simple taxon list for animal remains from the site – all of which come from burial contexts (Qi 1998: 184–185). The list provides quite general classifications and include pig (*Sus* sp.) specimens, one musk deer (*Moschus* sp.) mandible fragment, deer (*Cervus* sp.) bones, one dog (*Canis familiaris*) mandible, and four sheep (*Ovis* sp.) bones (see Table 1 for specimen counts). Surface remains witnessed by Li and Flad in 2005 may be parts of a camel cranium, but these were not found in context. Botanical remains from the site include specimens of wheat (*Triticum* sp.), barley (*Hordeum vulgare*), and rye (*Secale montanum*) (Li 1989; Li and Mo 2004; Wang Yiman 1992). These are among the earliest examples of these grains found east of the Tianshan Mountains, particularly if recent radiocarbon dates obtained from directly dating some of the wheat specimens are to be believed (Li and Mo 2004). These dates suggest that the Donghuishan floral remains are between 4500 and 5000 years old, considerably predating the Siba Culture. The only comparably early barley remains come from the site of Changguogou 昌果溝 near Changdu 昌都 in Tibet (see number 36 on Fig. 1), where oats have also been found dating to ca. 5.4 ka (Li Shuicheng n.d.). As for Donghuishan, further research is needed to clarify the site's cultural stratigraphy.

2.2 Huoshaogou 火燒溝 *and Gan'guya* 乾骨崖

The faunal remains found in burials at Donghuishan are securely associated with Siba Culture artifacts, however, and document an advanced stage in the exploitation of domesticated pigs and sheep in the region. It is not clear yet, however, whether other important Siba culture sites, such as Huoshaogou in Yumen 玉門 and Gan'guya in Jiuquan, contain similar faunal assemblages as their data have not yet been published. These two collections of faunal remains are being subjected to comprehensive analysis – the former by Huang Yunping at Peking University, the latter by Qi Guoqin from IVPP (Personal Communication between Li Shuicheng and both analysts, 2004). Preliminary information can be gleaned from summaries of early excavation results. A 1979 summary of work at Huoshaogou, for example, lists dog, pig, cattle, horse, and sheep among the site's fauna, with sheep being the most common (GSB1979: 142–143). Furthermore, artistic depictions of dogs and horses, and clay figurines of dogs and sheep, support the case for domestication of these taxa.

2.3 Later Remains

The situation with regard to later archeological cultures is not well understood because systematic studies of faunal remains have not yet been published. We might expect that some of the taxa exploited during earlier periods continued to be used by those responsible for the Siwa (Kayue) culture, and Shanma culture remains (Li and Shui 2002), which have been identified above Siba remains at Huoshaogou, may contain camel bones. Xindian culture remains at Zhangjiazui 張家嘴 in Yongjing (near the sites of Dahezhuang and Qinweijia discussed below), which like those of Shanma date to around 3.0 ka, are said to contain three horse teeth – but at this point in the chronology, the presence of domesticated horse would not be surprising (ZSKYGG 1980: 204). Most other Xindian remains, such as the newly published site report on the Hetaozhuang 核桃莊 site in Minhe 民和, Qinghai are cemetery sites without faunal remains (QSWKY *et al.* 2004).

Shajing culture fauna are only slightly better known. Shajing sites are mainly distributed in the eastern part of the Hexi Corridor (Pang 2002). The chronology of Shajing culture sites include an early phase, dating to the early Western Zhou period (ca. 3.0 ka) and a later phase that dates to the later Western Zhou and early Springs and Autumns period (ca. 2.8–2.4 ka). The fauna from this period may already include domesticated donkey and camel in addition to the cattle, sheep, horse triumvirate that was well established by the Western Zhou era. For example, although no formal report has been published on the faunal remains from Xigang 西崗 and Chaiwangang 柴灣崗, the report on these Shajing period cemeteries indicates that grave goods include heads of cattle, horse, and sheep as well as some donkey bones – all of which are thought to be domesticated (GSWKY 2001: 196). In addition, the authors indicate that the faunal assemblage from the sites contain the bones of other domesticates including camel, pig, dog and chicken. At the Shajing cemetery site of Hamadun 蛤蟆墩, burial chambers were blocked with heads of cattle, horse, and sheep (GSBWG and WDZ 1984; GSWKY 1990). For example, tomb M15 contained one horse head, 15 head bones from sheep and mountain

Table 1. Mammal species represented at various sites discussed in the text. Numbers given are NISP provided in report. Numbers in parentheses are MNI when provided. √ *= present but no quantities given. *=Thought to be domesticated.* *$^{?}$*= identified as domesticated but evidence is questionable.*
Section A: Hexi, Upper Yellow River, and Wei River Valley.

A	Region	Hexi Corridor		Upper Yellow River Valley					Wei River Valley								
General	Site	Donghuishan	Huoshaogou, Ganguyan, etc.	Dahezhuang	Qinweijia	Zhongri	Yangqu Shierdang	Xiangnagou	Shizhaocun					Xishanping			
									II	III	IV	V	VII	I	II	III	IV
	Approx. dates BP	4000-3500	4000-3000	4100-3900	4100-3900	5600-4000	5600-4000	5600-4000	6800-5800	5900-5500	5600-5200	5400-4700	4100-3900	8000-7400	7300-6900	5400-4700	4100-3900
	Pig (*Sus scrofa*)	27*	√*	194*	430*	11* (2)		1* (1)	√*	√*	√*	888*	256*	√*$^{?}$	√*	121*	83*
Bovidae	Cattle (*Bos* sp.)		√*	6*	38*	53*$^{?}$ (8)		4 (1)				√*	√*		√	√	√*
	Sheep (*Ovis* sp.)	4*	√*	56*	50*								√*				
	Mongolian Gazelle (*Procapra* sp.)					192*$^{?}$ (19)	22*$^{?}$ (3)	22*$^{?}$ (3)									
	Bharal (*Pseudois nayaur*)					1 (1)											
Cervidae	Deer (unid.)	17		4					√	√	√	√	√				√
	Red Deer (*Cervus elaphus*)					179 (9)	26 (2)	11 (2)						√	√	√	
	Roe deer (*Capreolus capreolus*)			1		295 (26)	35 (4)	21 (3)									
	Musk deer (*Moschus* sp.)	1				67 (19)	5 (3)	5 (1)		√	√	√		√		√	
Equidae	Equid (*Equus* sp)		√*$^{?}$	3*$^{?}$	√*$^{?}$							√*$^{?}$				√	
	Asian Wild Ass (*Equus hemionus*)				√												
	Donkey (*Equus asinus*?)		√*$^{?}$														
	Macaque (*Macaca* sp.)														√		

(Continued)

Table 1. (Continued)

A	Region	Hexi Corridor		Upper Yellow River Valley					Wei River Valley								
									Shizhaocun					Xishanping			
General	Site	Donghuishan	Huoshaogou, Ganguyan, etc.	Dahezhuang	Qinweijia	Zhongri	Yangqu Shierdang	Xiangnagou	II	III	IV	V	VII	I	II	III	IV
	Approx. dates BP	4000-3500	4000-3000	4100-3900	4100-3900	5600-4000	5600-4000	5600-4000	6800-5800	5900-5500	5600-5200	5400-4700	4100-3900	8000-7400	7300-6900	5400-4700	4100-3900
Canidae	Dog (*Canis familiaris)*	1*	√*	2*	√*	12* (3)		1* (1)				√*	√*	√*		√*	√*
Mustelidae	Weasel (*Mustela* sp.)				√												
Ursidae	Bear (*Ursus* sp.)											√					
	Asiatic Black Bear (*Selenarctos thibetanus)*													√			
	Feline (*Felis* sp.)											√					
Rodentia	Marmot (*Marmota* sp.)					113 (29)	7 (1)	5 (1)									
	Bamboo rat (*Rhizomys sinensis*)											√		√		√	
	Zokor (*Mylospalax fontanieri*)												√				
	Rat (*Rattus rattus*)											√		√			
	Total Specimens[1]	N/A	N/A	N/A	N/A	978 (128)	95 (13)	50 (13)	N/A	79	28	1202	301	140	N/A	245	101

[1] Total numbers given sometimes include other vertebrate bones (fish, birds, etc.) and therefore may not match the totals given for the quantities in the table.

Section B: Wei River Valley

B	Region	Wei River Valley (cntd.)															
General Taxon	Site	Beishouling	Anban		Fulinbao	Banpo	Jiangzhai				Baijiacun	Lingkoucun					Kangjia
			(Yangshao)	(Longshan)			I	II	IV Late Banpo	V Keshengzhuang		1	2	3	4	5	
	Approx. Dates BP	7300-6900	7000-6000	4800-4300	5500-5000	6900-5800	6800-6300	6300-6000	5600-5200	4500-4000	7500-6250	7300-7000	7000-6600	6600-6400	6400-6200	6200-5500?	4500-4000
	Pig (*Sus scrofa*)	√*$^?$	√*	√*	√*	√*	512* (85)	45* (8)	88* (12)	20* (4)	251*	(21)*	(8)*	(24)*	(16)*	(10)*	48*
Bovidae	Cattle (*Bos* sp.)	√*$^?$		√*$^?$	√*$^?$	√	72 (3)	12 (2)		2 (1)							√?
	Buffalo (*Bubalus* sp.)										166*$^?$						51*$^?$
	Caprinae (Sheep / Goat)											(1) *$^?$	(3) *$^?$	(3) *$^?$	(5) *$^?$	(3) *$^?$	2?
	Sheep (*Ovis* sp.)					√											36*$^?$
	Mongolian Gazelle (*Procapra* sp.)						7 (2)		4 (1)	4 (1)	36						
	Bharal (*Pseudois nayaur*)			√													
	Gazelle (*Gazella* sp.)												(1)				
Cervidae	Deer (unid.)						311 (19)	78 (7)	58 (5)	40 (6)							
	Red Deer (*Cervus elaphus*)	√			√						111						
	Sika (*Cervus nippon hortuloram*)		√	√	√	√	651*$^?$ (48)	26*$^?$ (7)	311*$^?$ (19)	101*$^?$ (11)		(9)	(6)	(9)	(5)	(5)	101
	David's Deer (*Elaphurus davidianus*)											(2)	(1)	(2)	(2)	(1)	
	Roe deer (*Capreolus capreolus*)	√			√												
	Musk deer (*Moschus* sp.)	√			√		6 (3)					(1)		(4)	(3)	(3)	
	Chinese water deer (*Hydropotes inermis*)	√	√	√	√	√	168 (21)	19 (4)	78 (16)	8 (1)	108						13

(Continued)

Table 1. (Continued)

B	Region	Wei River Valley (cntd.)															
General Taxon	Site	Beishouling	Anban		Fulinbao	Banpo	Jiangzhai				Baijiacun	Lingkoucun					Kangjia
			(Yangshao)	(Longshan)			I	II	IV Late Banpo	V Keshengzhuang		1	2	3	4	5	
	Approx. Dates BP	7300-6900	7000-6000	4800-4300	5500-5000	6900-5800	6800-6300	6300-6000	5600-5200	4500-4000	7500-6250	7300-7000	7000-6600	6600-6400	6400-6200	6200-5500?	4500-4000
	Equid (*Equus* sp.)					√											
	Macaque (*Macaca* sp.)	√					2 (1)										
	Porcupine (*Hystrix hodgsoni*)		√									(1)					
Canidae	Dog (*Canis familiaris*)	√*	√*	√*	√	√*	7* (2)		5* (2)	19* (1)	8*						21*
	Racoon dog (*Nyctereutes procyonoides*)	√	√	√		√	13 (5)	6 (1)	10 (4)	? (3)	12		(1)	(1)	(1)	(2)	37
	Fox (*Vulpes* sp.)	√				√											4
	Dhole (*Cuon alpinus*)						1 (1)										1

Mustelidae	Weasel (*Mustela* sp.)																1
	Eurasian Badger (*Meles* sp.)	√				√	12 (4)		1 (1)	1 (1)		(1)		(2)	(2)	(1)	
Ursidae	Bear (*Ursus* sp.)	√															
	Asiatic Black Bear (*Selenarctos thibetanus)*						3 (2)										2
Felidae	Feline (*Felis* sp.)					√	1 (1)				4						1
	Tiger (*Panthera tigris*)				√		1 (1)										1
	Rabbit (*Lepus* sp.)					√	1 (1)	1 (1)	5 (2)								13
Rodentia	Bamboo rat (*Rhizomys sinensis*)	√	√			√	5 (2)	5 (2)	4 (2)		10						3
	Pika (*Ochotona* sp.)					√											
	Zokor (*Myospalax fontanieri*)	√	√	√	√	√	14 (4)										
	Total Specimens[2]	N/A	N/A	N/A	N/A	N/A	2278	342	588	334	727	N/A (37)	N/A (20)	N/A (50)	N/A (36)	N/A (30)	

[2] Total numbers given sometimes include other vertebrate bones (fish, birds, etc.) and therefore may not match the totals given for the quantities in the table.

(Continued)

Table. 1 (Continued)

Section C: Arid North China, Tibet and Xinjiang..

C	Region	Arid North China											Tibet				Xinjiang
General	Site	Linziliang	Miaozigou	Daihai Region	Shihushan	Wangmushan shangpo	Dabagou	Zhukaigou					Karuo			Qugong	Chawuhu goukou
								I	II	III	IV	V	4	3	2		
	Approx. Dates BP	4800-4000	5800-5000	6700-5000	6500-6400	5500-5000	5800-5000	5000-4000	4000-3900	3900-3750	3750-3600	3600-3400	6000-5500	5000-4500	4500-4000	3750-3100	3000-1780
	Pig (*Sus scrofa*)	√*	46* (5)	√*	171* (15)	34* (4)	49* (5)	32* (8)	123* (19)	74* (19)	23* (4)	6* (2)	6*	19*	7*	√*	
Bovidae	Cattle (*Bos* sp.)	√*	42 (2)				22 (2)	46* (4)	95* (10)	37* (4)	59* (5)	2* (1)	56*	91*	20*		√
	Buffalo (*Bubalus* sp.)			√	520 (15)												
	Yak (*Bos grunniens*)															√*?	
	Sheep (*Ovis* sp.)							33* (5)	206* (27)	109* (15)	50* (8)	8* (1)				√*	√
	Mongolian Gazelle (*Procapra* sp.)	√	33 (2)		3 (2)		19 (3)						2	7	5		
	Goral (*N. goral*)								1 (1)				11	21	6		
	Serows (*Capricornus* sp.)													3			
Cervidae	Deer (unid.)	√															
	Red Deer (*Cervus elaphus*)		19 (6)	√	532 (22)	3 (1)	46 (1)		22 (5)	5 (1)	18 (2)		4	7	4	√	
	Sika (*Cervus nippon hortuloram*)	√			9 (3)		1 (1)										
	Therold's Deer (*Cervus albirostris*)															√	
	Roe deer (*Capreolus capreolus*)		65 (3)	√	866 (56)	26 (2)	36 (3)		10 (2)	9 (2)	6 (1)		12	3			
	Musk deer (*Moschus* sp.)	√														√	
	Chinese water deer (*Hydropotes inermis*)												55	85	35		

Equidae	Equid (*Equus* sp.)	√*$^{?}$	12 (2)				2 (2)										√
	Asian Wild Ass (*Equus hemionus*)						5 (1)									√	
	Bactrian camel (*Camelus bactrianus*)										1*$^{?}$ (1)						
	Macaque (*Macaca* sp.)												3				
Canidae	Dog (*Canis familiaris*)		√*		39* (3)[3]	10* (2)	30* (7)	3* (1)	4* (1)	7* (3)	8* (2)					√*	
	Racoon dog (*Nyctereutes procyonoides*)		√		56(4)												
	Fox (*Vulpes* sp.)		√		11 (2)									1			
	Dhole (*Cuon alpinus*)				2 (1)												
Mustelidae	Eurasian Badger (*Meles* sp.)				22 (3)				2(1)								
	Weasel (*Mustela* sp.)				1 (1)												
	Bear (*Ursus* sp.)				30 (3)		1 (1)				1 (1)						
	Feline (*Felis* sp.)								1 (1)								
	Ocelot (*Felis bengalensis*)				3 (1)												

(Continued)

[3] This total does not include four complete dog skeletons found in H12 at Shihushan (Huang 2001).

Table 1. (Continued)

C	Region	Arid North China											Tibet				Xinjiang
General	Site	Linziliang	Miaozigou	Daihai Region	Shihushan	Wangmushan shangpo	Dabagou	Zhukaigou					Karuo			Qugong	Chawuhu goukou
								I	II	III	IV	V	4	3	2		
	Approx. Dates BP	4800-4000	5800-5000	6700-5000	6500-6400	5500-5000	5800-5000	5000-4000	4000-3900	3900-3750	3750-3600	3600-3400	6000-5500	5000-4500	4500-4000	3750-3100	3000-1780
Lagomorpha	Rabbit (*Lepus* sp.)	√			5 (1)		√										
	Wooly Hare (*Lepus oiostolus*)														1		
Rodentia	Pika (*Ochotona* sp.)				3 (1)												
	Zokor (*Myospalax fontanieri*)				29 (4)	16 (1)											
	Ground Squirrel (*Spermophilus* sp.)				4 (1)	2 (1)											
	Rat (*Rattus rattus*)														1		
	Total Specimens[4]	N/A	234 (30)	16	2306 (138)	91 (11)	227 (36)	114 (18)	465 (67)	241 (44)	166 (24)	16 (4)	149	237	79	N/A	N/A

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[4] Total numbers given sometimes include other vertebrate bones (fish, birds, etc.) and therefore may not match the totals given for the quantities in the table.

goat. Some tombs also included donkey limb bones and, possibly, camel bones (GSWKY 1990: 2320).

Unfortunately, this is the sum total of published faunal remains from archeological sites in the Hexi Corridor. If we expand our view somewhat to the surrounding regions, several more sites with zooarcheological assemblages come into the picture.

3. Upper Yellow River Valley (Southern Gansu and Qinghai)

Crossing the Wushaoling 烏鞘嶺 Mountains to the south of Gulang 古浪, one leaves the Hexi Corridor and enters the Upper Yellow River valley in the region around modern Lanzhou 蘭州. Just west of Lanzhou, in Yongjing County 永靖, the Qijia sites of Dahezhuang and Qinweijia are two prominent sites with published faunal remains and based on their data we can start to characterize Qijia faunal exploitation.

3.1 Dahezhuang 大何莊

Dahezhuang lies on a terrace overlooking the confluence of the Yellow River and the Daxia 大夏 River, 1.5 km southwest of the Lianhua Community 蓮花公社 of Yongjing County. The Qijia culture remains at Dahezhuang have been radiocarbon dated using charcoal discovered in posthole number 2 from house floor F7 to 3570 ± 95 (ZK-15) and 3540 ± 95 (ZK-23) ^{14}C yr BP[3] (ZSKY 1991). Excavations at the site exposed both settlement-related features, including seven well-preserved house floors, 15 pits, and five "stone circles",[4] as well as 82 Qijia period burials. Thousands of pottery fragments, hundreds of stone tools, and a variety of tools and ornaments made of bone, stone, and bronze were discovered in excavations. Among these, a small, pottery animal figurine (possibly a sheep) and several pottery bird-head handles were found. Additionally, 266 animal bones from various contexts were recovered and analyzed. In total, seven animal taxa were identified at the site including pig (*Sus scrofa*), sheep,[5] cattle (*Bos* sp.), equid (*Equus* sp.), dog (*Canis familiaris*), deer (*Cervus* sp.), and roe deer (*Capreolus capreolus*) (ZKKYGG 1974). The collection of identified bones comprises mostly horn and tooth-bearing elements. Among these, mandibles of sheep or pigs were discovered in 12 burials. These number from as few as 2 to as many as 36 in a single grave. Complementing the sheep figurine, excavators uncovered 14 fragments of sheep scapulae that had been used in oracle bone divination in various contexts. Furthermore, an incomplete sheep skeleton was found west of F5, and a complete but headless skeleton of a female cow was uncovered 7 m east of house floor F1. Its midsection contained the bones of an unborn calf. The evidence supports the contention that both sheep and cattle were domesticated at the site. In addition, three horse mandibles were discovered in burial contexts. These three intentionally buried horse bones show that some horse mandibles were buried according to the same practices as were sheep and pig mandibles. This is the primary line of evidence that has been the basis for claims that horses were domesticated during the Qijia period. While this claim is credible, the current paucity of evidence begs for additional support from other sites.

3.2 Qinweijia 秦魏家

Qinweijia is one of these other sites and is also in Lianhua, Yongjing. It is a Qijia period cemetery that dates to about the same period as Dahezhuang. In total, 138 burials were excavated at the site, and an additional 73 pits and one "stone circle" were also uncovered during the excavation of the cemetery (ZKKYGG 1975). The majority ($n = 125$) of the graves contained burial objects, which include ceramics, stone and bone tools, ornaments, and animal bones. The analysis of the animal remains recovered from these burials identified pig, sheep, and cattle bones among the assemblage. Of the mandible fragments on which they base a comparison of the importance of various domesticates, sheep mandibles comprise 9.7% ($n = 50$), cattle comprise 7.3% ($n = 38$), and pigs comprise most of the remaining 83% ($n = 430$). Three fragments of sheep scapulae used as oracle bones were recovered from the burials, including one that had been placed inside a large, long-necked, double-handle jar (M23:2). In addition to these domesticated-animal bones, the analysts also reported remains of dog, weasel (*Mustela* sp.), and several equid bones, which are said to be Asian wild ass (*Equus hemionus*) and horse (*Equus feras/ E. domesticus*) bones, among the faunal assemblage. These bones are very fragmentary, however, and no detailed description or precise numbers have been reported. As we have discussed elsewhere, the evidence for horse domestication during the Qijia period remains circumstantial (Yuan and Flad 2005), but as will become clear below, the data do suggest that horses were found at almost all Qijia sites where the fauna have been examined although they are usually very few in number. The beginning of the use of other domesticated equids is even more poorly understood at present, and the Qinweijia remains, as reported, shed very little light on donkey use in East Asia.

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[3] Using the Online version of CalPal 2004 Ver 1.2 accessed in September, 2005 at http://www.calpal-online.de, these two dates are calibrated to 1924 ± 131 cal BC and 1887 ± 123 cal BC respectively. All other calibrated dates provided in this paper are calibrated using this software as well unless otherwise stated. Uncalibrated dates are given as conventional dates relative to AD 1950 and calculated using the Libby half-life of 5568 years.

[4] These might have been corrals, although they are identified as ritual areas due to their proximity to the cemetery and the discovery of oracle bones near the edge of two of the circles (F3 and F12).

[5] These results are reported in a quite preliminary fashion within an excavation report. As is frequently the case in Chinese archeological reports of this nature, the taxa are listed by their common names in Chinese. In this case the term *yang* 羊 is used, which is a general term that subsumes both sheep and goats. Although the authors have not examined these remains, the *yang* in this case are thought to be domesticated sheep for reasons that are discussed below.

3.3 Qinghai sites

Upriver to the west, the uppermost reaches of the Yellow River converge in eastern Qinghai Province. In this region, several excavated sites have established the sequence of Majiayao, Banshan, Machang, Qijia and Xindian cultural remains in the region including the important cemetery at Liuwan 柳灣 in Ledu 樂都 (Chang 1986:147; QSWGK and ZSKY 1984). Unfortunately, animal bones are rare from cemeteries such as Liuwan and no faunal assemblages have been reported from these sites. In addition, several sites associated with a culture now called the Zhongri 宗日 Culture have recently been investigated in the counties of Tongde 同德 and Xinghai 興海 (Chen *et al.* 1998; QSWG and HZMB 1998). Among the remains excavated from three sites: Zongri, Yangqu Ershidang 羊曲二十檔, and Xiangnagou 香那溝, 2364 animal bones have been examined and identified. The bones come from cultural levels that have been dated to the period between ca. 5.6–4.0 ka (An n.d.). Nine mammal taxa were identified in the assemblage including marmot (*Marmota* sp.), dog, wild pig, musk deer (*Moschus moshiferus*), roe deer (*Capreolus capreolus*), red deer (*Cervus elaphus*), cattle (*Bos* sp.), and two types of small bovids: Mongolian gazelle (*Procapra gutturosa*) and bharal (i.e., Himalayan blue sheep, *Pseudois nayaur*).

At the site of Zongri itself, 978 bones were recovered representing a minimum of 128 individual animals. Cervids comprise 55.3% (or 41.4% of the MNI) and marmots comprise another 11.6% (22.7% of MNI). According to these data only 5.4% are cattle bones and 19.6% are Mongolian gazelle. The Yangqu Ershidang assemblage is much smaller – only 95 identifiable bones. Of these, 22 are small bovids (MNI = 3). Lastly, the Xiangnagou site excavations recovered 50 identifiable bone fragments. Gazelle and sheep make up the majority of these remains ($n = 22$, MNI = 3). The various cervids and small bovids tend to be found naturally in habitats that are somewhat warmer, wetter, and greener than the current environment of the Gonghe 共和 Basin where these sites lie (An n.d.: 5). Deer of various sorts were the most significant components to the Zongri culture meat acquisition strategy. Nevertheless, An Jiayuan proposes that cattle and other bovids may have been domesticated based on both the number of specimens (which, in fact, is not very large) and a "significant number of young cattle and sheep in the assemblage" (An n.d.: 5). Although he goes on to discuss this as a significant site for the understanding of bovid domestication, we have our reservations considering the subjective nature of the determination that these animals were domesticated.

After the Zongri culture, sites in this region are associated with the Kayue 卡約 culture, which dates to the period between ca. 3.2–2.8 ka. Kayue culture sites such as Fengtai 丰台 are undergoing research at present and should be an additional source of information about the Bronze Age in this area as data are published (ZSKY & QSWKY 2004). The Xindian remains at Hetaozhuang and Zhangjiazui mentioned in the last section represent a different yet contemporary culture in this upper Yellow River region.

4. *Wei* 渭 *River Valley (Gansu/Shaanxi)*

Moving further to the south and east, the upper Wei River valley in eastern Gansu and Shaanxi Provinces contains many sites from various stages of the Neolithic that share significant characteristics with the Neolithic sites in the eastern part of the Hexi Corridor. In addition to the archeological cultures that are shared between the two regions, some sites in the Wei River valley provide characteristic archeological remains from earlier periods. At present, our understanding of the Neolithic cultural sequence for this region remains very similar to the sequence discussed in K.C. Chang's most recent edition of *The Archaeology of Ancient China* (1986: 141). It begins with material contemporary with, or slightly predating the earliest remains at Dadiwan 大地灣 (i.e. Dadiwan I), in Shaodian 邵店, Gansu, which is one of the more important excavated early sites in this region (Bettinger *et al.* 2005; Bettinger *et al.*, this volume; Fitzgerald-Huber 1983). The culture associated with the earliest remains at the site is now generally considered to be a variant of the Laoguantai 老官台 culture, which dates to ca. 8.5–7.0 BP. Alternatively, the term "Dadiwan culture" (ca. 8.0–7.4 ka) is occasionally used to refer to the early strata at the site. At Dadiwan, the cultural strata in total comprise a significant sequence of stratified remains for the early part of the Neolithic in this region from as early as 8.0 ka to around 5.0 ka (Gong 1988). The newly published comprehensive report (GSWKY 2006:861–910) contains a report on the fauna from this site that will add additional information to the picture of animal explotiation in the early stages of settled village life in this region, but this report was published between the writing of this chapter and the publication of this volume. The data from this analysis, therefore, have not been included in this descussion.

The Lower Beishouling 北首嶺 phase (ca. 7.3–6.9 ka) of the Laoguantai Culture is considered Late Laoguantai and is transitional to the Yangshao culture. Early Yangshao culture phases include the Lower Banpo 半坡 (ca. 6.9–5.8 ka)[6] and Shijia 史家 (ca. 6.3–6.0 ka)[7] variants, and finally the Miaodigou 廟底溝 (ca. 6.0–5.5 ka) culture. Following this period, the regional sequence with which we are most concerned comprises some of the same cultural phases as the Hexi Corridor discussed above: i.e., Shilingxia/Majiayao (ca. 5.6–4.65 ka), Banshan (ca. 4.8–4.3 ka), Machang (ca. 4.3–4.0 ka), Qijia (ca. 4.2–3.8 ka), Siba (ca. 3.9–3.5 ka), Siwa (ca. 3.3–3.0 ka), and Xindian (ca. 3.0 ka) cultures, although as one moves eastward towards the heart of the Central Plain, other regional cultures comprise this part

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[6] As pointed out by Loukas Barton in review comments on an earlier draft of this chapter, "in the Western Loess Plateau, the "Lower Banpo" or "Early Banpo" does not exist, save one possible, unpublished exception at the Heituya site in Li Xian. This is in stark contrast to the Wei River Valley east of the Liu Pan mountains, where the Early Banpo appears at Beishouling and sites further east." We thank him for further clarifying this aspect of the cultural sequence.

[7] As discussed by Chang (1986: 111), the Shijia phase is considered by some to fit between the Banpo and Miaodigou cultures and by others to be a variant of the Banpo Culture.

of the Neolithic sequence – perhaps most notably the Xiwangcun 西王村 (ca. 5.5–5.0 ka), Miaodigou II (ca. 5.0–4.6 ka), and Keshengzhuang II 客省莊二期/Shaanxi Longshan 陝西龍山 (ca. 4.5–4.0 ka) cultures. A full discussion of these cultures is well beyond the scope of this essay.

4.1 Shizhaocun 師趙村

In the uppermost reaches of the Wei River drainage, one of the sites with relatively Early Neolithic remains and published faunal data is the site of Shizhaocun, which is located 7 km west of Tianshui 天水 City on the banks of the Wei River in southeastern Gansu Province. Excavations at the Shizhaocun and nearby Xishanping 西山坪 identified nine phases, all of which have been radiocarbon dated (ZSKY 1999a: 306, 326). This work uncovered a total of 39 house foundations, 72 pits, 6 kilns, 27 tombs, 2 sacrificial deposits, and thousands of stone, jade, bone, and pottery objects. The 21 radiocarbon samples from the two sites provide the following calibrated date ranges: The earliest phase is Laoguantai (referred to in the report as Dadiwan I) (ca. 8.0–7.4 ka) and is only found at Xishanping. The next seven phases comprise the Shizhaocun sequence: Shizhaocun I (Lower Beishouling, i.e., Late Laoguantai) = 7.3–6.9 ka[8]; Shizhaoshan II (Banpo) = 6.8–5.8 ka; Shizhaocun III (Miaodigou) = 5.9–5.5 ka; Shizhaocun IV (Shilingxia) 5.6–5.2 ka; Shizhaocun V (Majiayao) = 5.4–4.7 ka; Shizhaocun VI (Banshan) = 4.5–4.0 ka; and Shizhaocun VII (Qijia) = 4.1–3.9 ka. Xindian Culture remains have also been discovered and date to ca. 3.4–3.0 ka.

At Shizhaocun, according to the faunal analyst Zhou Benxiong, remains from the lowest level (i.e., Shizhaocun I) are similar in character to Lower Beishouling phase materials but they do not contain faunal remains. Level 5 (Shizhaocun II) is associated with the region's Banpo phase and contains pig and deer bones. Miaodigou phase (ca. 5.9–5.5 ka) remains (Shizhaocun III) in level 4 include 76 bones, representing three general taxa: pig, deer, and musk deer (*Moschus mochiferus*). Level three (Shizhaocun IV) is assigned to the Shilingxia phase (ca. 5.6–5.2 ka) by the analyst and includes 28 bones representing the same three taxa as level 4. In the subsequent Majiayao (ca. 5.4–4.7 ka) culture stratum (Shizhaocun V), faunal remains are more abundant and represent 12 taxa. These taxa include deer, musk deer, wild and domestic pig, equid, dog, bear, bamboo rat (*Rhizomys sinensis*), feline, rat, turtle, and cattle. According to the analysts, the cattle were domesticated. A total of 1202 specimens were recovered from this stratum, the majority of which ($n = 888$) were pig bones. Dog and cattle bones comprise most of the remainder. The equid specimen is a single, fragmentary molar. Finally, the top level (Shizhaocun VII) is associated with the Qijia culture (ca. 4.1–3.9 ka) and contains bones from six taxa including deer, mole rat, pig, dog, cattle, and sheep, and the last four taxa are said to have been recently domesticated (Zhou 1999a: 336). Pigs again comprise the majority of the specimens ($n = 256$ of 301). The pigs from this stratum are said to have become smaller and frailer, possibly due to confined living conditions associated with intensive domestication.

4.2 Xishanping 西山坪

As mentioned, the lowest stratum at the nearby site of Xishanping, located 15 km west of Tianshui, are associated with period I at the Dadiwan site and identified as an example of the Laoguantai culture. A fairly wide variety of taxa are represented among the 140 animal bone specimens from this stratum including red deer (*Cervus elaphus*), musk deer, Asiatic black bear (*Selenarctos thibetanus*), bamboo rat, rat, dog, chicken, and pig. The pig bones from this level are said to be domesticated, and although the reason for this appellation is not given, we do not doubt this identification. In the next stratum (Xishanping II), associated with the Lower Beishouling phase, only a few bones were discovered. They include red deer, cattle, and pig bones and a macaque (*Macaca mulatta*) skull – which the excavators take to be evidence for much heavier foliage in the Tianshui area during the Middle Neolithic. Majiayao contexts at the site (Xishanping III) include bones, teeth and antlers from eight taxa including red deer, musk deer, bamboo rat, chicken, dog, equid, cattle, and pig. The pigs and dogs are thought to be domesticated based on the high frequency of pig bones (49.4% of the collection from this stratum) and the long history of dog domestication prior to this point (Zhou 1999a: 337). Cattle and chicken bones are quite sparse and equids are represented only by a single upper molar. The subsequent Qijia (Xishanping IV) period saw an increased reliance on pigs, which comprise 82% of the 101 specimens collected. Deer, cattle, and dog bones were also among the faunal remains from this period. For both of these sites, the fauna clearly show an increased reliance on domesticated pigs during the transition from the Majiayao to Qijia cultures. Cattle and sheep domestication may have begun during the Qijia period at these sites, but the evidence is not conclusive. The few equid remains are insufficient evidence for horse domestication but they do add further evidence at most Qijia culture sites contain a few equid bones – probably from horses (*Equus feras/E. domesticus*). This trend alone may support the contention that horses were among the domesticates exploited by Qijia people.

4.3 Beishouling 北首嶺

Moving down river along the Wei River, the site of Beishouling lies within Baoji 寶雞 City and comprises three phases of remains (ZSKY 1983). Excavations at the site

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[8] All the date ranges given here are based on ZSKY 1999a and may differ slightly from the general chronological span of the associated archeological cultures.

revealed 50 house floors, 67 storage pits, 4 kilns, and 451 tombs. The houses are generally semi-subterranean in structure and rectangular or circular in shape. They tend to all face toward the central area of the site in a pattern similar to that seen at other sites in the region such as Jiangzhai and Banpo (see below). Burials comprise shaft pit graves for adults and urn burials for children. The former are found in a separate cemetery area at the site. The features and associated artifacts all date to the Neolithic era and are separated into three phases of occupation. The earliest phase serves as a reference for the Late Laoguantai phase known as "Lower Beishouling" mentioned above and contains wood-charcoal based radiocarbon dates of 6280 ± 120 ^{14}C yr BP (ZK-0519, 5227 ± 144 cal BC) and 6150 ± 120 ^{14}C yr BP (ZK-0534, 5087 ± 149 cal BC). The middle phase belongs to the Banpo phase and has been dated with six samples, the earliest of which dates to 5970 ± 120 ^{14}C yr BP (ZK-0516, 4878 ± 147 cal BC) and the most recent to 5320 ± 100 ^{14}C yr BP (ZK-0499, 4158 ± 113 cal BC). The latest phase has been dated with two dates of 5240 ± 100 ^{14}C yr BP (ZK-0498, 4093 ± 120 cal BC) and 4980 ± 85 ^{14}C yr BP (ZK-0533, 3800 ± 103 cal BC), the last of which was a bone sample.

Excavated first from 1958 to 1960, and then again in 1977 and 1978, faunal remains have been reported from the latter excavations (Zhou 1983). In addition to domestic chickens (*Gallus gallus*), and several fish and shellfish specimens, investigators have identified the following species in the site's remains: bamboo rat (*Rhizomys sinensis*), mole rat (*Muospalax fontanieri*), macaque (*Macaca mulatta*), dog (*Canis familiaris*), badger (*Meles meles*), raccoon dog (*Nyctereutes procyonoides*), fox (*Vulpes vulpes*), bear (*Ursus arctos*), pig (*Sus scrofa*), red deer (*Cervus elaphus*), musk deer (*Moschus moschiferus*), Chinese water deer (*Hydropotes inermis*), roe deer (*Capreolus capreolus*), and bovine (*Bos* sp.[9]). Among these, the deer species, bamboo rat, and macaque, suggest a warmer more forested environment, and the fish, water deer, raccoon dog, and water deer bones indicate more nearby wetlands. The assemblage contains several species that are thought to have been domesticated including some of the pig, cattle, and chicken. Unfortunately, the remains are not discussed in detail by phase. The circumstantial evidence for domesticated pig includes the large percentage of the assemblage that pigs comprise, the existence of a relatively large number of juvenile pigs, and the discovery of a pottery pig head. The 24 upper M3 molars and 25 lower M3 molars recovered from the site are rather large,[10] however, and so the investigators are therefore equivocal in their opinion of the degree to which the pigs were, in fact, domesticated. In any case, domesticated pigs are already known from Cishan in Hebei (Yuan and Flad 2002), which is roughly contemporary with the Lower Beishouling remains, so the presence of both domesticated and wild pigs is not remarkable. The attestation of domesticated dogs is even less so. In contrast, even in the latter phases, the presence of domesticated cattle would still be a rather early example, but some doubt that these bones actually represent domesticated individuals (Huang 2003a: 608).

4.4 Fulinbao 福臨堡

Also near Baoji is the Neolithic site of Fulinbao (BSKG and SSKYBG 1993). The site is located on a terrace overlooking the Wei River and excavations between 1984 and 1985 uncovered 137 pits, 12 house foundations, 12 kilns, and 45 graves at the site. Hundreds of pottery fragments and over 1000 bone and stone tools comprise the artifact collection. In addition, 180 bone fragments have been studied from the site (Wu Jiayan 1993). The excavations identified three chronological phases, all of which belong to the Yangshao culture. Radiocarbon dates have been produced for the second and third of these phases. For the latest phase, dates produced from shell remains of 4510 ± 110 ^{14}C yr BP (ZK-2056, 3202 ± 158 cal BC) and 4270 ± 85 ^{14}C yr BP (ZK-2058, 2865 ± 139 cal BC) put this phase in the latter half of the sixth millennium BP (calibrated). A date for the second phase of 4270 ± 135 ^{14}C yr BP (ZK-2141, 2891 ± 207 cal BC), but this date is questioned by the excavators, who suggest, instead, that this phase is contemporaneous with the late part of the Miaodigou culture and dates to approximately 5.7–5.3 ka.

Based on the 180 faunal remains from the site, 10 taxa have been identified. These include pig (*Sus scrofa*), musk deer (*Moschus moschiferus*), Chinese water deer (*Hydropotes inermis*), roe deer (*Capreolus capreolus*), red deer (*Cervus elaphus*), and sika (*Cervus nippon* – identified as *Cervus [Pseudaxis] grayi* in the report), cattle (*Bos* sp.), wolf (*Canis lupus*), tiger (*Panthera tigris*), zokor (*Myospalax fontanierii*), and pheasant (*Phasianus colchicus*). Other than the pigs, which are likely domesticated, the collection from Fulinbao does not shed substantial light on the trajectories of domestic animal use in this region.

4.5 Anban 案板

The same can basically be said of the site of Anban, which is located on a terrace 4km south of a village of the same name in Fufeng 扶風 County, central Shaanxi (XDWKZ 2000). After its discovery in 1953, the site was investigated several times, and six seasons of excavations between 1984 and 1993 examined five areas at the site. In four of these seasons, the excavators recovered large numbers of artifacts, including bone and stone implements, ceramics, and over 300 fragmentary animal bone specimens. These were

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[9] These remains were identified as *Bos exiguus* by Zhou Benxiong in the site report (Zhou 1983: 146). It is not clear from the published material whether this identification refers to bones that would now be called *Bison exiguus* or whether they represent a species of *Bos*.

[10] The upper M3 molars average 35.4mm long, 20.6mm wide, and 12.3mm tall. The lower M3 molars average 38.0mm long, 15.9mm wide and 12.1mm high.

interspersed among pits and house floors from several different chronological periods. Together, the site comprises three archeological strata dating to the Late Yangshao culture, the early Longshan era, radiocarbon dated to 4060 ± 85 ^{14}C yr BP (ZK-1378, 2648 ± 147 cal BC) and 3980 ± 105 ^{14}C yr BP (ZK-1377, 2497 ± 164 cal BC), and Zhou period (post-1050–221 BC) (Zhang 1988; XDWKZ 2000). All the faunal material comes from the Yangshao and Longshan period levels (Fu 2000). In addition to mollusk fragments, and turtle and chicken (pheasant?) bones, the faunal assemblage comprises 10 mammal taxa including: bamboo rat (*Rhisomys* sp.), porcupine (*Hystrix* sp.), mole rat (*Myospalax fontanieri*), dog (*Canis familiaris*), raccoon dog (*Nyctereutes procyonoides*), pig (*Sus scrofa*), Chinese water deer (*Hydropotes inermis*), sika (*Cervus nippon* identified in the report as "*Psuedaxis hortulorum*"), cattle (bovidae) and caprines that appear similar to bharal (*Pseudois* sp.). The pig bones are thought to represent both wild and domestic individuals. The identification of some as domesticates is based on their abundance and the relatively small size of the pig bones. Some specimens, however, are thought to be wild pig bones based primarily on their large size. The chicken/pheasant and cattle are said to be possible domesticates (West and Zhou 1988), but the latter comprise only three tooth-bearing mandibles.

4.6 *Banpo* 半坡

Further downstream in the area around the modern city of Xi'an, archeologists have unearthed abundant remains from the Middle Neolithic period. Among the most important sites in this region is the Banpo site in Xi'an's eastern outskirts. Banpo covers an area of approximately 5 ha and contained materials from two principal phases: Early Banpo and Late Banpo. The Early or Lower Banpo remains include two areas of residential structures comprising 46 houses of various shape and size. These were mostly circular, although others were rectangular. Additionally, kilns and 174 graves were found at the site. Over 5000 tools and hundreds of ceramic vessels were recovered during the excavations (ZKKY & SSXBB 1963; Yang 2004: 51). Many of the latter were painted with zoomorphic designs that are now icons of Chinese Neolithic art.

Although the analysts take pains to point out the importance of separating animal bones by context, the faunal report does not summarize the faunal remains from different phases at Banpo with any quantitative data (Li and Han 1959). The total assemblage comprises dog (*Canis familiaris*), pig (*Sus scrofa*), cattle (Bovidae), sheep (*Ovis* sp.), equid (*Equus* sp.), sika (*Cervus nippon*), Chinese water deer (*Hydropotes inermis*), bamboo rat (*Rhizomys sinensis*), pika (*Ochotona* sp.), rabbit (*Lepus* sp.), gazelle (*Gazella* sp.), badger (*Meles meles*), raccoon dog (*Nyctereutes procyonoides*), fox (*Vulpes* sp.), some feline (*Felis* sp.), zokor (*Myospalax sp.* identified in report as *Siphneus* cf. *fontanieri*, these are small rodents resembling mole-rats), fish, and at least two types of bird: golden eagle (*Aquila* sp.), and chicken (*Gallus* sp.). The cattle, sheep, and equid bones at the site are quite few in number and, according to the investigators, were probably all from wild animals (Li and Han 1959: 185). Otherwise, they take no opinion as to whether the chicken was domesticated. The presence of bamboo rat and Chinese water deer indicate a climate that was warmer and wetter than the present in the Wei River valley during the middle part of the Neolithic.

4.7 *Jiangzhai* 姜寨

Slightly further to the east in Lintong County lies the site of Jiangzhai, which is roughly contemporary with Banpo and is one of the best known and most thoroughly discussed Middle Neolithic sites in all of China (XBB *et al.* 1988). The village discovered at Jiangzhai was nearly complete and covered 5ha. Outside of a surrounding ditch, several distinct cemetery areas were also located. Excavations at the site show that the remains are divided into five phases corresponding to the following sub-phases of the Yangshao culture: Banpo (I), Shijia (II), Miaodigou (III), Xiwangcun (IV), and finally the Keshengzhuang (V) culture. The Banpo settlement phase comprises the best preserved phase of the residential area. About 120 house structures surround a central plaza at the site and they are clustered into five groups, each of which faces toward the central plaza and includes a large structure and a dozen or more small or medium-size structures. The excavations of this village recovered hundreds of personal ornaments, bone, shell, horn and pottery tools, nearly 1000 pottery vessels, and over a million pottery sherds (Chang 1986: 116–119; Yang 2004: 51–52).

A total of 3542 bone fragments were examined in the zooarcheological study of the site (Qi 1988). The collections come from phases I, II, IV, and V. The majority of these bones ($n = 2278$, or 64%) were discovered in deposits from the earliest phase and reflect, primarily, the relatively complete nature of the phase I deposits. With the exception of a few pig teeth and deer bones found in burials, which were a part of funeral offerings, the bones were found in other features associated with everyday activities at the site such as pits, kilns, and activity surfaces. The assemblage as a whole comprises 29 different taxa. These include two fish species and three bird species (including chicken), two rodent taxa (bamboo rat and mole rat), macaque (*Macaca mulatto*), rabbit (*Lepus* sp.), dog (*Canis familiaris*), raccoon dog (*Nyctereutes procyonides*), dhole (a.k.a. Asiatic wild dog, *Cuon alpinus*), bear (*Selenarctos thibetanus*), badger (*Meles meles* and *Arctonyz collaris*), two felines (*Felis* sp. and *Panthera tigris*), pig (*Sus scrofa*), sika (*Cervus nippon*), musk deer (*Moschus moschiferus*), Chinese water deer (*Hydropotes inermis*), Mongolian gazelle (*Procapra gutturosa*), and cattle (*Bos* sp.) (see Table 1 for NISP and MNI). The pig remains from the first phase are identified as domesticates primarily based on the age of the individuals, 83% of which are less than 2 years old. Measurements of third molars from the collection also demonstrate that they are smaller than those of wild swine. The analysts also suggest that the sika from the site may have been herded and penned (Qi 1988: 536). This claim is based on the abundance of sika at sites from this period, but more importantly on the young age of the deer population – 40% are 2.5–3 years of age. The two large pens in the open central area of the Jiangzhai village are thought to possibly have been used for penning deer. As for bovids, both cattle and caprid bones are rare at the site, and it is possible that they were all from wild individuals.

4.8 Baijiacun 白家村

Baijiacun is located in also located in the lower Wei River valley in Lintong County, 26 km northeast of the county seat (ZSKY 1994). Four cultural levels were identified at the site, the middle two of which contained faunal materials (Zhou 1994). The earlier of these, stratum 3, is associated with the Laoguantai culture, whereas stratum 2 dates to approximately 7.0 ka. Nine bone and shell samples from the site provide radiocarbon dates that range between 7525 and 6200 ^{14}C yr BP (ZSKY 1991: 263–264). The site's earliest remains, therefore, predate the Banpo phase of the Middle Neolithic Yangshao culture. With the exception of several pig bones and perforated water deer teeth, most of the faunal material found at the site was recovered from pits. A total of 2209 specimens was analyzed, 727 of which could be identified to some degree of specificity. The identified taxa comprise, chicken, fish, mollusk, and the following mammals: pig, dog, water buffalo (*Bubalus* sp.), red deer (*Cervus elaphus*), Chinese water deer (*Hydropotes inermis*), Mongolian gazelle (*Procapra gutturosa*), raccoon dog (*Nyctereutes procyonoides*), some cat (*Felis* sp.), and bamboo rat (*Rhizomys sinensis*). Pig and water buffalo are the most common bones in the collection, followed by bones of red deer and Mongolian gazelle (see Table 1). The analysts identify the pig and buffalo as domesticated along with dog and chicken. These pig remains if truly the bones of domesticates, are among the earliest domesticated pigs in China, although still later than the earliest dates for Cishan. The water buffalo remains would also be among the earliest domesticated remains but if these remains are, in fact, *Bubalus* bones, we think that it is highly unlikely that they were domesticated animals. In addition to the abundance of specimens, Zhou Benxiong has also suggested that the relatively small size of the specimens and their overall morphology are reasons to identify the water buffalo as domesticates.

4.9 Lingkoucun 零口村

The Lingkoucun site is also located Lintong, Shaanxi Province, 19km east of the county seat. Remains at the site come from five different phases of the later Yangshao culture (7.3–6.2 ka) (SSKY 2004). The earliest period, which dates to ca. 7.3–7.0 ka, is contemporary with the Baijiacun material mentioned above. The second phase, dating to about 7.0–6.6 ka, is referred to by some as the Lingkoucun phase of Yangshao, as it post-dates the Baijiacun remains. It is roughly contemporaneous with the earlier part of Lower Banpo phase and is a regional variant of the Yangshao culture. This phase contains semi-subterranean rectangular house foundations with rounded corners, double rooms, and doors facing to the southeast. Burials contain single, primary skeletons in shaft pit graves. The ceramics differ somewhat from Baijiacun and Banpo ceramics in that certain tripod forms typical of Baijiacun ceramics are absent from the collection and surface treatment styles differ (SSKY 1999:13). Phase 3, dating to approximately 6.6–6.4 ka and the fourth phase (ca. 6.4–6.2 ka) contain remains similar to the Lower Banpo phase of the Yangshao culture. Finally, phase 5 dates to about 6.2–5.5 ka.

Among the remains recovered from the site, analysts identified bones representing a minimum of 157 individuals of 13 taxa[11] (SSKY 2004: 283–285, 347–348, 381–382, and 450–453; Zhang *et al.* 2004). These data are provided by phase in Table 1. The taxa identified at the site include: bamboo rat (*Rhizomys sinensis*), porcupine (*Hystrix hodgsoni*), raccoon dog (*Nyctereutes procyonoides*), badger (*Meles meles*), musk deer (*Mochus* sp.), David's deer (*Elaphurus davidianus*), sika (*Cervus nippon*), pig (*Sus scrofa*), gazelle (*Gazella* sp.), cattle (Bovinae), and, according to the analysts, Caprinae. Most common in all phases are pig bones – although their dominance declines slightly over time, followed by *Cervus hortulorum.* The identification of Caprinae is particularly significant, but somewhat confusing. "Caprinae" is the Latin name for the sub-family that includes sheep and goats and is therefore a rather noncommittal attribution. Nevertheless, the Chinese taxa identified in the report is *shanyang* 山羊, which means goat, i.e., *Capra* sp. This identification, if accurate, is quite remarkable because goats have not been identified anywhere else at this early a date. Sheep and goat are, it should be noted, notoriously difficult to distinguish and we are hesitant to assign too much significance to this discovery until it is supported by other data – particularly if the intention of the authors was, in fact, to merely claim that these specimens were "Caprinae." In any case, at least 15 sheep/goats represented in the assemblage from Lingkoucun are mostly sub-adults, which leads the investigators to the conclusion that they are most likely domesticated. If correct, this is important regardless of whether the animals are sheep or goats because it suggests a very early date of caprine domestication ca. 7.0 ka. We are not, however, convinced that the

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[11] In the report for the site of Lingkoucun, two separate results of faunal analysis are published. Both sets provide only MNI counts and not NISP data, and the two data sets have many small inconsistencies. For example, the MNI numbers provided in Table 47 (SSKY 2004: 451) indicates that the five phases at the site have MNI for *Cervus hortulorum* of 9, 6, 9, 5, and 5, respectively. Zhang and colleagues (Zhang *et al.* 2005: 530) however, list the respective MNI counts as 11, 5, 9 and 3 (excluding phase V). It is unclear why these discrepancies exist. In Table 1 we have used the counts from the site report (SSKY 2004) instead of the discussion by Zhang *et al.*

evidence for domestication is yet strong enough for such a conclusion to be drawn.

4.10 Kangjia 康家

The Kangjia site in Lintong dates to the Keshengzhuang phase (4.5–4.0 ka) of the Longshan culture and includes several rows of connected houses in one portion of the site (Liu 1994; 2004b: 49). In total, excavations at the site uncovered 33 house foundations in the Longshan strata as well as numerous pits, human skeletons, bone, stone, and pottery objects and large numbers of sherds (SSKYKK 1988, 1992). A detailed report of faunal remains from excavations in 1990 has provided some sense of the overall faunal assemblage at the site (Liu *et al.* 2001; Liu 2004b: 51). This study identified 20 mammal taxa at the site in a collection of 3046 faunal specimens recovered from a 10 × 10 m unit (T26). Of these bones, 2790 are mammal bones whereas the rest comprise bird ($n = 36$), fish ($n = 36$), reptile ($n = 1$) and mollusk ($n = 192$) specimens,[12] Among these, 357 bones were subjected to detailed identification. In addition to two mollusks, two fish, five birds, and one reptile taxa, the mammal taxa include: bamboo rat (*Rhizomys sinensis*), rabbit (*Lepus* sp.), tiger (*Panthera tigris*), an unidentified feline (*Felis* sp.), fox (*Vulpes* sp.), dog (*Canis familiaris*), dhole (*Cuon alpinus*), raccoon dog (*Nyctereutes procyonoides*), weasel (Mustelidae), black bear (*Selenarctos thibetanus*), pig (*Sus scrofa*), Chinese water deer (*Hydropotes inermis*), sika (*Cervus nippon*), Bovids (either *Bos* sp. or *Bubalus* sp., or both), and caprids (either *Ovis* sp. or *Capra* sp., or both). *Cervus nippon* were the most common taxon in the assemblage, followed by bovinae. The investigators were able to identify some of the latter definitively as water buffalo but although no *Bos* specimens were definitely present, they do not reject the possibility that some of the individuals were cattle. They further suggest that the buffalo may have been domesticated and used primarily as draft animals. That pigs were domesticated is confirmed by the predominance of juveniles in the assemblage, a pattern that is also seen among the caprid bones. The investigators identify both goat and sheep in the assemblage, although only two bones, which are not identified in the published report, are definitively identified as goat (Liu *et al.* 2001: 21). A total of 21 bones are identified as sheep (*Ovis* sp.), and the remainder of the 38 sheep/goat bones are undifferentiated (in Table 1 we include these in the "sheep" count). If the two bones in question are, in fact, goat bones, they would be an early example in the region (depending on whether goats were, in fact, present at Linkoucun as discussed above). Further evidence is needed to substantiate the claim for domesticated goat exploitation at during the Longshan in this region.

These sites provide the most complete data from the Wei River valley to date and allow us to establish a basic outline of domesticated animal use in the areas to the south and east of the Hexi Corridor during the middle to Late Neolithic periods.

5. Arid North China

Moving to the east of the Hexi Corridor to the arid semi-desert and desert areas that straddle the modern political units of Gansu, Ningxia, and Inner Mongolia, we find several sites that, while not particularly early, provide some additional information concerning the transition to animal domestication. Since the sequence of archeological cultures for this large region is complex and fluctuating as more research is done, and at present is frankly not very well worked out, we will focus on several sites without attempting a premature, brief summary of the cultural sequence for the region.

5.1 Linziliang 林子梁

One of the very few published analyses of faunal remains from this region concerns the site of Linziliang in Caiyuan 菜園 Village, Haiyuan 海原 County, in the Ningxia Autonomous Region. The site was excavated in 1987 as part of a project that investigated several sites in the Caiyuan area (NWKY and ZLBK 2003). The excavations at the site uncovered a dense cluster of superimposed strata with pits ($n = 57$), semi-subterranean house floors ($n = 13$), a kiln, two graves, and an urn burial. Ground-stone, microlithic, and bone tools, and numerous fragmented pottery comprise the majority of the archeological material. The pottery from periods III and IV at Linziliang are similar to those from Zhukaigou period I (discussed below), and radiocarbon dates place the Linziliang remains between 4400 and 4150 ^{14}C yr BP (NWKY and ZLBK 2003:333). Along with the site of Mayingziliang 馬纓子梁 in the same area, the Linziliang remains are associated with the contemporaneous Banshan (ca. 4.8–4.3 ka) and Machang (ca. 4.3–4.0 ka) cultures of Shaanxi and Gansu. Small numbers of fragmentary bones make up the Neolithic faunal assemblage from the site (Han 2003). Ten taxa were identified in the brief report including several that relate to the current discussion: Mongolian gazelle (*Procapra gutturosa*), pig (*Sus* sp.), cattle (*Bos taurus*), and equid (*Equus* sp.). Other identified mammal taxa include sika (*Cervus nippon*), musk deer (*Moschus moschiferus*), other deer (*Cervus* sp.), rabbit (*Lepus* sp.), and rodent (Muridae). Although the analyst admits that the collection strategy used did not ensure that the recovered bones were a representative sample, based on the available material he states that sheep, pig, cattle, and sika were probably the most common mammals consumed. He further posits that pig and cattle were domesticated. One cattle scapula was used for pyromantic divination. The equid bones from

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[12] This is but one example of quantitative data provided in faunal reports not adding up. The total numbers of specimens according to gross taxa equal 3055, but the total number of specimens provided in the same sentence is 3046 (Liu *et al.* 2001: 4). It is not clear why this discrepancy exists, but such inconsistencies are not uncommon.

the site comprise only a lower molar and phalange bones and are insufficient to determine whether they represent horses that may have been domesticated – which we believe is doubtful.

5.2 Miaozigou 廟子溝 *and Dabagou* 大壩溝

Somewhat more robust faunal assemblages were collected from the sites of Miaozigou and Dabagou (Huang 2003a). Both sites are located about 8 km south of the Huangqihai 黃旗海 lake in Qahar Youyi Forebanner (Chayou Qianqi 察右前旗), Ulanqab Meng (Wulanchabu meng 烏蘭察布盟), Inner Mongolia, at the foot of the Yinshan 陰山 Mountains. These sites, just northeast of the northeastern corner of the great bend in the Yellow River, are affiliated with Miaozigou phase of the Yangshao culture (NWKY 2003; Wei Jian 1991). Excavations at Miaozigou between 1985 and 1987 uncovered 52 well-preserved dwellings, with a clearly distinguishable settlement pattern, 139 pits and 42 graves. At Dabagou, located about 6 km west of Miaozigou, excavations at two localities in 1988 and 1992 uncovered a total of 45 dwellings, 129 pits, a trench encircling the settlement area, and two graves. The Miaozigou and Dabagou site remains, which comprise type collections for the Miaozigou culture, are divided into three phases. Six calibrated radiocarbon dates produced for nearby but related sites suggest that the first phase dates to ca. 5.8 ka, the second to ca. 5.4 ka, and the third to ca. 5.0 ka (NWKY 2003: 649–650).

Fauna recovered from excavations at the two sites were not very abundant but were generally similar to one another. At Miaozigou, 234 specimens were recovered representing a minimum of 30 individuals. In rough order of abundance, the fauna include roe deer (*Capreolus capreolus*), pig (*Sus scrofa*), cattle (*Bos* sp.), Mongolian gazelle (*Procapra gutturosa*, identified in the report by the sub-genus *Prodorcas*), red deer (*Cervus elaphus*), equid (*Equus* sp.), and small numbers of dog (*Canis familiaris*), raccoon dog (*Nyctereutes procyonoides*), fox (*Vulpes* sp.), and various rodents, birds, and mollusks. At Dabagou, 227 bones representing a minimum of 36 individuals were analyzed. The assemblage is similar to Miaozigou. It includes pig (*Sus scrofa*), red deer (*Cervus elaphus*), roe deer (*Capreolus capreolus*), dog (*Canis familiaris*), cattle (*Bos* sp.), Mongolian gazelle (*Procapra gutturosa*, also identified as *Prodorcas*), sika (*Cervus nippon*), bear (*Ursus* sp.), equid (*Equus* sp.), wild ass (*Equus hemionus*) and small numbers of various rodents, rabbits, birds, and mollusks. According to Huang Yunping, the cattle bones from Miaozigou are similar in shape to *Bos primigenius*, but clearly smaller. They are, however, larger than domesticated cattle found at sites such as Yinxu 殷墟 in Anyang 安陽 and Xiawangang 下王崗 in Xichuan 淅川, Henan 河南, and Qucun 曲村 in Quwo 曲沃, Shanxi 山西 (Huang 2003a: 600). Among the equid bones, two from Miaozigou can be used to determine age. They reflect horses of around 3.5 and 2–3.5 years, respectively. The size of the bones is similar to those of Prezwalski's horse (*Equus przewalskii*). Huang concludes that the cattle and horses at the sites are not domesticated whereas dog and pig are thought to have been. She proposes, however, that some of the pig bones found at the site were, in fact, from wild pigs based on the size of the molars of some specimens. The bones and antlers of red deer, wild horses, and wild cattle in particular were used for the production of bone tools.

5.3 The Daihai 岱海 *Region*

Only slightly to the west, recent research in the basin around lake Daihai in Liangcheng 涼城 County has involved the investigation of a number of sites attributed to three periods of the Yangshao culture (ca. 6.7–5.0 ka) and others associated with the Laohushan 老虎山 culture (ca. 4.5–4.3 ka). The Yangshao sites in the area include: Wangmushan poxia 王墓山坡下, Wangmushan pozhong 王墓山坡中, Hongtai poxia 紅台坡下, Hongtai poshang 紅台坡上, Dongtan 東灘, and Huzishan 狐子山 (NWKY and BDZKYZJK 2003). In total, excavations at these sites exposed 41 house foundations, 43 pits, a moat, and numerous artifactual remains from the Yangshao era. These have been divided into three phases: I (6.7–6.4 ka); II (6.2–5.6 ka); and III (5.6–5.0 ka). During phases I and II, site layouts suggest small cohesive communities. Only in the third phase is there any evidence of the clustering of house structures around several larger buildings. Culturally, this phase appears connected to the Miaozigou culture discussed above.

About 500 years later in the same area sites are affiliated with the Laohushan culture. Five sites in particular have been the focus of research on this cultural complex: Laohushan 老虎山, Yuanzigou 園子溝, Xibaiyu 西白玉, Mianpo 面坡, and Damiaopo 大廟坡 (NWKY 2000). Several of these sites, including Laohushan, Xibaiyu, and Damiaopo have stone enclosures on hilltops in addition to the ubiquitous residential structures, which are deep, cave like dwellings dispersed along the slopes of hills with their entrances invariably facing downward. A total of 259 houses have been discovered in the 9000 m^2 excavated at the five sites along with 61 pits, 11 kilns, and 10 burials. The sites seem to have been intentionally placed in defensible positions on hill slopes and some of the sites have stone encircling walls that further enhance their defensibility.

The excavations at these various sites have uncovered a wealth of archeological material including ceramics, stone and bone artifacts, and faunal remains. An extremely cursory faunal report on the bones from Yangshao contexts at Wangmushan poxia, Wangmushan pozhong, Hongtai poshang, and Dongtan comprise a total of 16 bones (Huang 2003b). These include possible water buffalo (*Bubalus bubalis*) bones at Wangmushan poxia, roe deer, red deer, and pig. Additionally, more extensive discussions of the fauna recovered from Shihushan 石虎山 and Wangmushan poshang 王墓山坡上 are available and discussed further here.

5.3.1 Shihushan 石虎山

The Shihushan site was one of the localities investigated by the collaborative project between the Inner Mongolia

Institute of Archaeology and the Kyoto Committee on Chinese Archaeological Research (NWKY and RJZKY 2001; NWKY and RJZKYDDK 2001a). The site is located 2 km southeast of the village of Shuanggucheng 双古城 in Ulanqab Meng on a terrace 1348–1368 m.a.s.l. Excavations and coring in 1993, 1995, and 1996 have uncovered archeological remains at the site that include an encircling trench, 20 house foundation, 36 pits, and one burial. The most significant remains comprise the Shihushan I assemblage. A radiocarbon sample for this phase was collected from plant matter found in the surrounding ditch and dates Shihushan I to ca. 6500 ka,[13] The remains from this locus lie in the northwestern portion of the site, slightly to the southeast of the crest of the hill on which the site is located. It covers an area of about 1.5 ha and is separated from Shihushan II by as slight depression. Excavations explored the ditch around Shihushan I and discovered six house foundations, 12 storage pits, and a sacrificial pit.

Among the artifacts and ecofacts recovered during these excavations were 2306 animal bones (Huang 2001). These represent a minimum of 138 individuals from 18 distinct animal taxa. The taxa include: pig (*Sus scrofa*), water buffalo (*Bubalus bubalis*), Mongolian gazelle (*Procapra gutturosa*, identified in the report by the sub-genus *Prodorcas*), red deer (*Cervus elaphus*), roe deer (*Capreolus capreolus*), sika (*Cervus nippon*), dog (*Canis familiaris*), raccoon dog (*Nyctereutes procyonoides*), fox (*Vulpes* sp.), dhole (*Cuon alpinus*), Eurasian badger (*Meles meles*), bear (*Ursus arctos*), ocelot (*Felis bengalensis*), weasel (*Mustela* sp.), rabbit (*Lepus* sp.), pika (*Ochotona* sp.), zokor (*Myospalax fontanieri*), and ground squirrel (*Spermophilus* sp.) (see Table 1).

5.3.2 Wangmushan poshang 王墓山坡上

Wangmushan poshang is very close to the Shihushan site, 2 km from the village of Quanbuzi 泉卜子 at the northern foot of Wangmushan Mountain on top of the northwestern slope of round mesa (NWKY and RJZKYDDK 2001b). The slope where the site is located is covered with archeological loci, which have been divided into three clusters: upper-slope (poshang 坡上), mid-slope (pozhong 坡中), and lower-slope (poxia 坡下), each of which is chronologically distinct. The upper-slope site covers about 1.1 ha. between 1300 and 1310 m.a.s.l., about 120 and 15 m in elevation from the mid-slope locality. The lower-slope site is 300 m distant and about 25 m lower. The upper-slope site slopes downward from east to west fairly steeply. Excavations in 1987, 1989, 1992, and 1995 exposed 21 house foundations, 29 pits, and three burials. With the exception of one house and the three graves being of Qing 清 Dynasty date, the remainder of the material relate to the Yangshao culture – approximately contemporaneous with the Middle to Late Miaozigou culture.

Among the archeological remains at the site, excavators recovered 108 animal bones, among which eight taxa were identified. These include pig (*Sus scrofa*), dog (*Canis familiaris*), red deer (*Cervus elaphus*), roe deer (*Capreolus capreolus*), zokor (*Myospalax fontanieri*), ground squirrel (*Spermophilus* sp.), bird, and fish. The most common among these is the pig ($n = 34$), four of which can be aged. These include one over 2 years in age, two that were about 1 year old when killed, and one half-year piglet. Other animals were hunted, an activity further documented by stone and bone projectile points found at the site.

Both of these sites have a much higher percentage of wild animals than purported domesticates. The domesticates at both sites comprise dog and possibly pig. The dogs are few in number but morphologically are clearly different from wild dogs and there is a pit at Shihushan (H12) with four complete dogs that appears to be a sacrificial deposit. Dogs were probably an important hunting companion at these sites. As for pigs, Huang Yunping (2001) points out that at Shihushan they are not a numerically important part of the assemblage. The morphology of the Shihushan pig mandibles suggests that they are domesticates, however, and the size of the third molars likewise confirms the existence of small, domesticate-sized pigs (Nishimoto 2001). Furthermore, Nishimoto suggests that there was a mix of wild and domesticated swine in the Shihushan assemblage, and that domesticates comprise over 50%. At Wangmushan, the relatively large number of pigs and their young age suggests a more important role for domesticated pigs at this site. Finally, the water buffalo identified at Shihushan are noteworthy but are not discussed further. Their status as wild or domesticated animals is not clear.

5.4 Zhukaigou 朱開溝

Zhukaigou is located in Ejin Horo Qi (Yijin Huoluo Qi 伊金霍洛旗) of central Inner Mongolia. The site's excavators divide the remains into three major phases with five sub-phases, the first of which dates to the Longshan period (ca. 5.0–4.0 ka),[14] The next three sub-phases date to the first half of the fourth millennium BP and are much more completely preserved. The last phase dates to the early part of the Shang Dynasty period (ca. 1650–1045 BC) (NWKY 1988). Four additional radiocarbon dates from the site provide benchmarks for the second millennium chronology,[15] but the

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[13] The date provided [Sample RH-64, i.e., Beta-111809] is an oak seed, which, after adjusting for the C13/C12 ratio, provides an uncalibrated date of 5670 ± 60 ^{14}C yr BP. This is calibrated to 4518 ± 70 cal BC (or 6468 ± 70 calBP).

[14] Although the first phase is said to date to the "Later Longshan" (Linduff 1995: 133), two radiocarbon dates from this phase suggest that initial occupation may have occurred in the early third millennium or even earlier (BK-79053: 4320 ± 90 ^{14}C yr BP or 2957 ± 138 cal BC; WB84-78: 4680 ± 80 ^{14}C yr BP or 3485 ± 104 cal BC) (ZSKY 1991: 59).

[15] These samples include one that is from the last sub-phase of Zhukaigou Phase II (BK-80028, 3320 ± 70 ^{14}C yr BP or 1606 ± 76 cal BC), and three others (WB84-76, 3220 ± 70 ^{14}C yr BP or 1509 ± 77 cal BC; WB84-77, 3190 ± 85 ^{14}C yr BP or 1469 ± 97 cal BC; and 3420 ± 70 ^{14}C yr BP or 1734 ± 98 cal BC) with unspecified sub-phase associations (ZSKY1991: 60).

dates provided in Table 1 are merely rough estimates of the successive periods. The material remains from this site demonstrate increasing inter-regional interaction by the Shang period after a long period of successive occupation phases by an indigenous bronze using culture (Linduff 1995; Wang Lewen 2004). The site includes 82 house foundations, 151 pits, and 329 burials distributed among the five phases.

A total of 1002 faunal specimens representing a minimum of 157 individuals have been recovered from three areas of the site and analyzed (Huang 1996). These specimens include 11 different taxa including pig (*Sus scrofa*, $n = 258$, MNI = 52),[16] sheep (*Ovis* sp., $n = 406$, MNI = 56), cattle (*Bos* sp., $n = 239$, MNI = 24), dog (*Canis familiaris*, $n = 22$, MNI = 7), red deer (*Cervus elaphus,* $n = 45$, MNI = 8), roe deer (*Capreolus capreolus*, $n = 25$, MNI = 5), goral (*Naemorhedus goral,* $n = 1$), weasel (*Meles meles,* $n = 2$, MNI = 1), leopard (*Panthera pardus*, $n = 1$), bear (*Ursus* sp., $n = 2$, MNI = 1), and Bactrian camel (*Camelus bactrianus*, $n = 1$ – a tooth fragment). The faunal report presents a detailed phase-by-phase breakdown of the abundance of these taxa and analyses of the age profiles and measurements of the pig, sheep and cattle bones. These three taxa remain dominant throughout the occupation of the site and their relative proportions do not change significantly over time. There are slight changes, however, with cattle being relatively most common during the first phase and sheep and pig become more abundant during the second phase. As only 16 bones were recovered from the so-called Shang period phase, the relative abundance of these domesticates is hard to assess. In addition, although not included in the total counts listed above, the faunal remains from Zhukaigou also include a significant number and wide variety of oracle bones. This collection is interesting due to its variability. The 51 total divination bones not only comprise scapulae of the ubiquitous cattle (32), deer (11), pig (4), and sheep (2), but a camel scapula and a bear scapula were used as well. The camel bone in particular further confirms the presence of camel at the site (and demonstrates that these scapulae were not included in the NISP and MNI counts since only a single camel tooth is listed in the chart), and although this single example cannot speak to the question of domestication, particularly when bones of wild animals such as deer and bear were used for this practice, nevertheless it provides a rare example of early camel bones excavated from a relatively early context.

6. Tibet

Archeology in Tibet is rather peripheral to the present discussion but worth a brief note. Relatively thorough summaries of Tibetan archeology can be found in several recent publications (Huo 2000; Aldenderfer and Zhang 2004). The sites of Karuo and Qugong are the most important and well known of the early sites in the region.

6.1 *Karuo* 卡若

The regions south of the Hexi Corridor include the vast region of the Tibetan plateau and associated mountain regions. We previously mentioned archeological remains from the upper Yellow River valley in Qinghai. Other early remains are found much further to the south, in Tibet proper. Among these, the site of Karuo in Camdo (Changdu 昌都) is particularly important to our current understanding of the archeology of the Himalayan uplands as it is one of the few early highland sites that has been published and discussed more comprehensively (Aldenderfer, this volume; Aldenderfer and Zhang 2004: 30; XZWGW and SDL 1985). Karuo was excavated twice in 1978 and 1979. Three radiocarbon dates are provided in the site report, one each in levels 4, 3 and 2. These dates 4810 ± 100 ^{14}C yr BP (ZK-0815, 3567 ± 124 cal BC) for level 4, 4160 ± 100 ^{14}C yr BP (ZK-0812, 2730 ± 128 cal BC) for level 3, and 3820 ± 80 ^{14}C yr BP (ZK-0819, 2282 ± 125 cal BC) for level 2, give a rough span for the Karuo culture of 6.0–4.0 ka and make the remains roughly contemporaneous with the Majiayao, Banshan, and Machang phases of the Yangshao culture. Forty-one radiocarbon dates are provided in the *Report of C-14 Dates from Chinese Archaeology* (ZSKY 1991: 243–249). They range from as early as 5120 ± 300 ^{14}C yr BP (ZK-0816, 3926 ± 327 cal BC) to as late as 3540 ± 105 ^{14}C yr BP (WB79–53, 1889 ± 135 cal BC). The majority of these dates predate 4.0 ka, after calibration.

In addition to an extensive mix of artifacts and some well-preserved architectural features, some representative animal bones were collected during the excavations. The analysis specifies the element used in identification very rarely – a clear indication that quantification was not the objective of the analysts – and a taxa list has been produced for the collection (Huang 1980). Subsequently, in the site report, rough quantities for each of the major taxa are given (Huang and Leng 1985: 166). The animals represented at the site include birds such as falcons (*Falco* sp.) and eagles (*Anser* sp.), and mammals including red deer (*Cervus elaphus*), roe deer (*Capreolus capreolus*), goral (*Naemorhedus goral*), serow (*Capricornus* sp.), Mongolian gazelle (*Procapra picticaudata*), Chinese water deer (*Hyrdopotes inermis*), woolly hare (*Lepus oiostolus*), rat (*Rattus rattus*) and some other rodents, fox (*Vulpes* sp.), macaque (*Macaca* sp.), unidentified bovid (*Bos* sp.), and pig (*Sus* sp.), which are supposed to be domesticated. As shown in Table 1, cattle and water deer are the most common taxa at the site, followed by goral and pig. Although there is no reason to think that these numbers are actually representative of species abundance, the data suggest that the subsistence strategies remained relatively stable at Karuo over time.

6.2 *Qugong* 曲貢

The site of Qugong, located 5 km north of Lhasa is a second significant Neolithic site from the southern part of Tibet (Aldenderfer and Zhang 2004: 31–32; ZSKYXG &

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[16] The totals given here are NISP and MNI figures for each taxa for the entire site. Counts for each phase are provided in Table 1.

XZWGW 1991a, 1991b; ZSKY and XZW 1999). According to the results of eight radiocarbon dates from the site, the occupation dates to somewhere within the time span of 3.75–3.1 ka (see dates provided in Aldenderfer and Zhang 2004: 28). Faunal remains discovered at the site include Yak (*Bos grunniens*), domesticated sheep (*Ovis aries shangi*), musk deer (*Moschus moschiferus*), red deer (*Cervus elaphus*), Therold's deer (*Cervus albirostris*), wild and domesticated pig (*Sus scrofa*), Tibetan ass (kiang *Equus hemionus kiang*), dog, and some birds (Zhou 1999b).

Among these fauna, the yak is most important for our present discussion. The yak at Qugong are thought to be domesticated because of the large number of specimens, the relatively small size of the animals, and the location of Qugong outside the purported natural range for the species. As discussed further below, yaks are thought to have been domesticated in the Qinghai region based, primarily on genetic data. At present, very little zooarcheological data have been brought to light relevant to this issue. In the preliminary report for excavations at the site of Dalitaliha 搭里他里哈[17] near Nomhon (Nuomuhong 諾木洪) in Dulan 都蘭 County, Qinghai dating to approximately 3.0 ka,[18] a clay figurine purported to be a yak was discovered in excavation in the 1950s (QSWGW & ZSKYQ 1963: 42). Also at this same site, remnants of a structure thought to be a wood-fenced corral were identified. Within the fenced area, a cattle skull was identified. This skull is said to be from a wild animal, but the presence of a pen suggests a degree of domesticated animal use (QSWGW & ZSKYQ 1963: 26). The pen is said to have been filled with ovicaprid dung and some camel dung as well (Mair 2003: 173). Additionally, fragments of the hubs of spoked wheels have been identified at the site, evidence that suggests the use of wheeled vehicles and perhaps draft animals (Barbieri-Low 2000: 11–12; QSWGW & ZSKYQ 1963: 41). According to some scholars, other domesticates such as horse and goat were probably introduced with Buddhism in the first millennium AD (Aldenderfer and Zhang 2004: 41).

7. Xinjiang

The prehistoric period of Xinjiang 新疆 is only recently becoming better understood, but there remains little evidence for human activity in the region until about 4000 years ago,[19] Several relatively early sites have been discovered and excavated in the region, including Qawrighul (Gumugou 古墓溝) and the cemetery at Xiaohe 小河 in the Lop Nur (Luopu Hai 羅布泊) region, but few fauna are reported in detail for these sites despite the fact that human remains have been the focus of much research and discussion (Han 1986, 1993). Qawrighul is said to have sheep/goat and cattle remains associated with pastoralism and dating to the fourth millennium BP (Chen and Hiebert 1995: 253). In contrast, excavations at Xiaohe by Fölke Bergman in 1934 and further research in 2002–2003 uncovered well-preserved remains of 140 wooden coffins and their contents, but little evidence of faunal exploitation (Bergman 1939; XWKY 2004). Given the fantastic state of preservation at the site, wooden tools, weapons, sculptures and coffins, and other perishable grave goods such as clothing, feathers, basketry, burial shrouds, foot and head gear, one might expect good bone preservation for faunal remains. None are reported, however.

7.1 Chawuhu goukou 察吾乎溝口

Somewhat more is known about the fauna from this important site. A publication detailing the burials discovered at the sites along the Chawuhu stream – a tributary to the Karaxahar River (Kaiduhe 開都河) – documents graves scattered among five cemeteries in the county of Hejing 和靜 on the northern edge of the Tarim Basin (XWKY 1999). Cemetery number 1, located 3 km north of the village of Houshancun 后山村, which includes the hamlet of Jueluntuergen 覺倫吐爾根, in Haermodun 哈爾莫墩, and about 2 km from the mouth of the gulley, comprises around 700 graves, 240 of which have been excavated. Dating to the mid to late part of the third millennium BP, this cemetery is substantially later than most of the other sites we have been discussing in this summary. The cemetery belonged to a lineage that existed from the Western Zhou (ca. 1045–771 BC) to the Springs and Autumns period (770–476 BC). Analysis of the faunal remains from this cemetery has shown, not surprisingly, that domesticated cattle were exploited at the site and comprise 20% of the faunal collection based on MNI calculations (An and Yuan 1998). Sheep, although present at cemetery number 1, are not common, although they comprise a substantial proportion (67%) of the bones from the nearby cemetery 3, which dates to the Eastern Han (AD 25–220). Most importantly for the present discussion, horse bones are common at both sites. At cemetery 1, 78% of the fauna buried in the cemetery were horses. Although animals that are placed in burials cannot be considered a representative sample of animals exploited by a society, the abundance of horse remains here, and the custom of burying horses in cemeteries, adopted from procedures used at other Bronze Age sites further to the east, is the earliest indication of domesticated horse use in the arid regions of Xinjiang.

8. Summary – Animal Domesticates in Arid China

The history of animal domestication in China is long and involves different processes for different animals. Shelach's

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[17] A place name meaning "Fire Mountain" (灰山) or "Fired Mountain" (火烧过的山) in Mongolian (Li Shuicheng).

[18] This site is still not well dated. Seven cultural levels have been reported from excavations at the site. A fragment of an aba textile was recovered from level 5 and radiocarbon dated to 2905 ± 140 cal BC. The stratigraphically lower levels 6 and 7 are clearly earlier than this based on their constituent ceramics. These lowest levels, therefore, almost certainly predate 3.0 ka.

[19] Mair (2004: 2) argues that the Tarim basin was never occupied prior to ca. 4.0 ka. See Chen and Hiebert (1995) for an excellent and thorough overview of the prehistoric archeology of the region and the various archeological cultures that have been identified.

(2000) call for a focus on local trajectories of animal and plant domestication recognizes that the process varied widely from one region to another. With this in mind, we reflect here on the possible process by which each of the following animals was adopted as a domesticate in arid northwest China and the Hexi Corridor: dogs, pigs, cattle and yaks, sheep and goats, camels, and equids. The currently available evidence from the region suggests that, with the possible exceptions of the camel and yak, most domesticated animals were introduced to the region as domesticates from other areas. Pigs and dogs seem to have been introduced from points east. Cattle, sheep, goats, and horses seem to have entered the area as domesticates from the west or north. Although the climatic conditions discussed by Madsen and Elston in this volume may have set the stage for the intentional cultivation of plants at the margins of their natural zones of dispersal, particularly during periods of highly voluble climate fluctuation, the same process does not seem to be transferable to the domestication of animals in this region.

8.1 Dog

Dogs are the domesticate about which we know the least concerning the process and timing of domestication relative to the amount of information available. Dogs most likely entered a symbiotic relationship with humans as early as ca. 20 ka in various places in Eurasia and have a long history of domestication in China. All three sites we discuss in the Hexi Corridor – Dahezhuang, Qinweijia, and Donghuishan – contain dog remains, and these are all thought to have been domesticated dogs. Similarly, many of the other sites from adjacent regions contain dog bones (see Table 1), and in almost every case, with the exception of Fulinbao in the Wei River valley, the dogs are either demonstrably domesticates or assumed to be so. The earliest domestication of dogs in China probably occurred near the end of the Pleistocene in mobile hunting and gathering communities and preceded agriculture, as represented by sites such as Nanzhuangtou 南庄頭 in Xushui 徐水 County, Hebei 河北 (Olsen *et al.* 1980; Underhill 1997: 114). Morphological analyses of dog remains excavated at two sites in the area discussed in this paper show that different breeds of dogs developed in Northwest China in antiquity (Nobuo *et al.* 1998). Genetic evidence on modern dog populations further suggests that domesticated dogs emerged from wolf populations in various areas (Leonard *et al.* 2002; Vilà *et al.* 1997). Domesticated dogs, therefore, seem to be present in the Hexi region from the earliest part of the Neolithic occupation of the area. Whether they were initially brought in by immigrant agriculturalists or adopted by indigenous populations is currently a matter of pure conjecture.

8.2 Pig

As demonstrated by recent genetic studies of pigs, multiple domestications most likely took place (Larson *et al.* 2005). In fact it is possible that multiple domestications of pig took place within China. At present, the earliest evidence for domesticated pigs in China comes from the site of Cishan in Henan (Yuan and Flad 2002). As mentioned, however, evidence from Kuahuqiao is roughly contemporaneous with the Cishan data and may, in fact, be a separate example of incipient pig domestication in East Asia. As far as the northwest is concerned, domesticated pigs were most likely introduced from the south and east, i.e., the Wei River Valley. As mentioned above, pig remains in the Dadiwan culture (8.0–7.4 BP) levels at Xishanping seem to be domesticates and it is certain that domesticated pigs were raised and exploited in the Hexi area prior to the Qijia culture era at the end of the third millennium.

8.3 Cattle

The aforementioned Qijia culture is a momentous period in the northwest region when it comes to animal domestication. Previous summaries of domesticated cattle use in the Hexi area have identified the Qijia culture sites of Qinweijia and Dahezhuang in Yongjing and Shizhaocun in Tianshui as locations with the earliest substantial evidence of domestication (see discussions above). Xishanping IV levels, contemporary with the Qijia also contain domesticated cattle. In contrast, the analysts of the bones from the Beishouling site in Baoji and the Jiangzhai site in Lintong argue that the cattle at these sites were domesticated (Qi 1988; Zhou 1983), but this conclusion has been doubted by others (Huang 2003a: 608). Other early cattle remains have been found in ca. 5000 year old strata at Fulinbao and at the Longshan site of Anban, but their status in regards to domestication is not confirmed. Nevertheless, pre-Qijia domesticated cattle are identified in the Majiayao levels at Shizhaocun. In addition, the faunal remains from Zhongri culture sites in Qinghai dating to ca. 5.6–4.0 ka contain purportedly domesticated cattle, and cattle sacrifices are reported from Santaisi, dating to around 4.5 ka (Murowchick and Cohen 2001: 56–57). Additionally, cattle from the earliest levels at Zhukaigou (ca. 5.0–4.0 ka) are said to be domesticates. In general, the use of domesticated cattle in China is thought to have begun between 4000 and 5000 years ago, slightly earlier than the Qijia period.

Currently, the lack of well-documented early or Middle Neolithic sites in the Hexi region tremendously obscures the processes by which populations and their subsistence patterns changed in this area over time. When it comes to cattle, this region is potentially a very important one for understanding the adoption of domesticated cattle in other regions of China. Cattle were first domesticated from wild *Bos primogenius* stocks in Africa and West Asia (Bradley *et al.* 1998). Genetic and zooarcheological evidence for cattle (*Bos taurus*) domestication points to northeast Africa by 10 ka (Marshall and Hildebrand 2002) and the Near East by the same time or slightly earlier (Troy 2001). Indian cattle (*Bos indicus*) may have been separately domesticated around the same time in South Asia (Loftus *et al.* 1994), but were clearly present as domesticates in Northwestern South Asia by 7.5 ka (Meadow 1996). Scholars have long assumed that domesticated cattle were introduced to China from points west or south, and the timing of the current evidence does not reject this possibility. Nevertheless, considerably more data is needed to evaluate the routes, process, and accuracy of this hypothetical introduction. Furthermore, it is clear that wild cattle stocks did exist in China prior to the existence of fully domesticated varieties and it is not out of the question that they played some contributive role in the emergence of domesticated cattle in China.

8.4 Water Buffalo

While on the subject of cattle it is necessary to mention the presence of water buffalo at four sites discussed here – although none of them are within the Hexi region itself. Baijiacun in the Wei River valley, dating to ca. 7.5–6.25 ka, the Longshan culture site of Kangjia (ca. 4.5–4.0 ka), and the Daihai regions sites of Shihushan (ca. 6.5–6.4 ka), and Wangmushan poxia (Yangshao culture, i.e., ca. 6.7–5.0 ka), all include bones identified as water buffalo, and the Baijiacun and Kangjia examples have been identified as domesticates based on morphology, frequency, and size. Such early dates for water buffalo domestication have been questioned and are currently under investigation (Liu 2004a; Liu *et al.* 2004a, 2004b; Yang and Liu 2004). Clearly, wild water buffalo were indigenous to parts of China, but it is not yet clear whether they were ancestral to the subsequent domesticated buffalo populations. Most scholars identify two general taxa – swamp buffalos and river buffalos, and argue for indigenous domestication of swamp buffalos in China or Southeast Asia (Barker 1997; Chen and Li 1989; Lau *et al.* 1998). It remains possible that all early water buffalo remains from China represent wild animals, however. Accordingly, river buffalo may have been first domesticated in South Asia around 4.5 ka (Cockrill 1981; Kikkawa *et al.* 1997: 197) and then brought to eastern Asia through Southeast Asia in subsequent periods. More research on existing evidence should allow for a clearer picture in the future.

8.5 Yak

This bovid seems to have been domesticated first in the northern part of Tibet, but the timing and process of this domestication are completely unclear since very little zooarcheological evidence of early yak exploitation currently exists. Evidence from the Qugong site is the earliest published material as it dates to as early as 3.75 ka. But it is suspected that the natural habitat of wild yak, between the altitudes of 2000 and 5000 m.a.s.l., is primarily in the Qinghai region, and perhaps initial domestication of yaks took places further to the north than Qugong (Wiener *et al.* 2003). Secondary evidence such as dung (Rhode and Madsen, this volume) and DNA analyses (e.g., Qi *et al.* 2004) are the only lines of evidence currently being brought to bear on this issue.

8.6 Sheep/goat

Sheep and goats were probably first domesticated in the Near East, perhaps in the Zagros area or surrounding regions, around 10,000 years ago (Zeder and Hesse 2000). Unlike many other domesticates, genetic evidence for goats suggests that they may have been only domesticated once (MacHugh and Bradley 2001). In China, evidence for sheep precedes that for goats, but neither seems to have been domesticated indigenously, as the wild bovids in the region such as bharal, Mongolian gazelle, goral, and serow, were not the progenitors of domesticated taxa. As noted elsewhere in this volume (Madsen *et al.*), sheep (*Ovis* sp.) were found in the Hexi Corridor as part of the Qijia suite of domesticates by the beginning of the fourth millennium BP. At all three Hexi Corridor sites discussed above (Dahezhuang, Qinweijia, and the Siba culture site of Donghuishan) domesticated sheep have been identified in the strata from this period. The contemporaneous levels at Shizhaocun likewise contain domesticated sheep. At earlier sites in the Wei River valley, sheep remains have also been identified occasionally. For example, the Banpo faunal assemblage contained sheep and dates to ca. 6.9–5.8 ka. But these are not necessarily domesticated animals. Likewise, the Linkoucun caprines bones date to between 7½ and 5½ thousand years ago. Sheep bones identified at the Longshan site of Kangjia and many other Longshan sites are common and more confidently thought to be domesticated individuals. The Zhongri culture site of Xiangnagou likewise contained sheep bones from more than 4000 years ago, and these sheep are thought to be domesticates. Other sites in which sheep remains are identified as domesticates include Qugong and Zhukaigou, both of which also date to between 3½ and 4 ka. Together these data suggest that domesticated sheep were introduced into the northwest region along with wheat sometime between 4 and 5 ka.

All of the earliest domesticated caprines in published reports are ovids (sheep) rather than caprids (goats) with two exceptions: The collection from Kangjia is said to contain caprids. Likewise, the recently published collection from Linkoucun is said to be mostly "Caprinae," and these are said to be domesticated. As mentioned above, the Kangjia goat remains comprise only two specimens and the "goat" identification is somewhat tenuous. As for the Linkoucun bones, we believe that the attribution is intended to indicate the sub-family "Caprinae" rather than the genus "*Capra.*" If so, it is quite possible that the Linkoucun caprines are wild species such as bharals, serows, or gorals. In that case their early date would not be so remarkable.

8.7 Camel

Bactrian camels (*Camelus bactrianus*) are native to the Altai region and surrounding regions including the Ordos and Mongolian regions to the east, and they are thought to have been domesticated in this general area (He 1986). Although some have suggested a much broader range, the native range of wild camels probably extends no further west than central Kazakhstan (Potts 2004: 145). After initial domestication in this region, the range of Bactrian camels expanded to cover regions to the west, including Bactria, and they emerged as important beasts of burden used throughout Central Asia (Potts 2004: 147). John Olsen (1988) mentions camelid remains from the Baotou region, just north of the bend in the Yellow River in Inner Mongolia, but contrary to the conjecture by Daniel Potts (148), there is no reason to suspect that these were anything but wild camelids as this would be well within the presumed natural habitat of the so-called Bactrian camels,[20] In fact, the camel remains (limited to one tooth) at Zhukaigou mentioned above (Huang 1996) demonstrate that camel remains older than 3 ka have been found (and published) from this area. Other possible anecdotal evidence points to camel exploitation in the Hexi region during the same millennium at sites such as Donghuishan and Huoshaogou. Although some suggest a date of domestication around 4000 years ago (He 1986), evidence from further west, including terracotta models of camels pulling carts and faunal remains, document domesticated camels in Turkmenistan as early as 5 ka (Potts 2004: 149). By the subsequent millennium, between 4000 and 3000 years ago, contemporary with the Zhukaigou remains, Bactrian camels were already being exploited as far west as Syria (Potts 2004: 150). Given the suspected dates of domesticated Bactrian camel use in Central Asia, we should suspect equally early evidence from north and northwest China (see also Madsen *et al.*, this volume). At present, we only possess zooarcheological evidence from the Shajing culture (i.e., ca. 3 ka) site at Chaiwan'gang (GSWKY 2001) and the Hamadun Cemetery in Gansu (GSWKY 1990), which firmly establish a *terminus ante quem* for domesticated camel use in this area. Slightly earlier evidence may be the reported camel dung remains from the end of the second millennium enclosure at Dalitaliha in Qinghai. As one of us has discussed previously (Yuan 2004: 58) additional archeological evidence for domesticated camel use can be found in the inventory of the Pingling 平陵 aristocratic tombs dating to the Zhaodi 昭帝 period of the Western Han (74 BC). In niches off an entrance passage to sacrificial pit number two, 54 large mammals were placed as offerings: 33 camels, 11 cattle, and 10 donkeys.

8.8 Donkey

The 10 donkeys mentioned from the Han period Pingling tombs in Shaanxi also provide some of the earliest conclusive evidence for donkey domestication (Yuan 2004: 58). As in the case of the camel, however, it is probable that domesticated donkey use in Northwest China predates this period. This is suggested by the donkey bones found in burials in the first millennium Shajing Cemetery at Hamadun in Xinjiang. The domesticated donkey has its origins in Africa around 5000–7000 years ago (Beja-Pereira *et al.* 2004). Since it is not a descendent of the Asian wild ass, the wild ass bones found at Qinweijia and Dabagou do not have any necessary connection to animal domestication. As is the case with most domesticates in Northwest China, donkeys were probably introduced from the outside, in this case almost certainly from the west.

8.9 Horse

The variety of evidence of horse remains in China is discussed in detail elsewhere (Linduff 2003; Yuan and Flad 2003, 2006). These data show that domesticated horses only appear in the central parts of China in the Late Shang period, but that horse remains are found in peripheral regions to the north and west somewhat earlier. Horses may have been domesticated in Central Asia earlier than this, most likely sometime near 5 ka, or slightly earlier (Brown and Anthony 1998; Levine 1999, Levine *et al.* 2003; Mashkour 2006). In northwest China, horse remains are few in number. The Qijia culture is frequently referred to as having domesticated horses (see Madsen, this volume). It is true, in fact, that all Qijia sites for which faunal analysis has been conducted do have horse remains. Both Dahezhuang and Qinweijia, discussed above, contain horse bones. But they are not numerous. It has also been reported, in the Dahezhuang publication, that the site of Huoshaogou contained horse remains that were sacrificed in burials (Linduff 2003: 144; ZKKYGG 1974). We believe that future data will confirm that Qijia communities were regularly exploiting horses and suspect that it will constitute a form of domestication. At present, however, these data remain sparse. By the Late Shang, horses are known from Yinxu in Anyang and contemporaneously, in Pre-dynastic Zhou sites like Fengxi 澧西, in Chang'an, Shaanxi, domesticated horses were found outside the Shang core in cultural deposits (Yuan and Xu 2000: 252). Subsequently, in the Western Zhou period, horse burials are ubiquitous (see, e.g., ZSKY 1999b: 78–95). The northwest, including the Hexi Corridor, may have been a conduit for the introduction of horses into central parts of China. It is equally likely, however, that the horses found in the Late Shang Central Plains arrived through communication with groups to the north, towards present day Inner Mongolia. The Qijia horse remains are suggestive of early horse domestication in Northwest China, but are not necessarily connected to the subsequent horse use further to the east.

9. Conclusion

Given the multiple lines of evidence discussed at the beginning of this paper that reflect, in a variety of ways, the

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[20] Incidentally, Baotou is nowhere near the region of the Xinglongwa Culture which Potts inexplicably links to these remains claiming "the locales would have been difficult to reach without the use of the camel."

nature of animal domestications, it is vital to the study of this question that faunal collections made at archeological sites be large and as comprehensive and representative as preservation conditions will allow. It is a lamentable fact that zooarcheology has traditionally not been a significant component of the research design employed at Chinese archeological sites. In many cases animal remains are collected only sporadically and opportunistically, and little attention is paid to the consistency of collection strategies. This must change if more is to be known about the exploitation of animals in the areas of China discussed above.

As is clear from the varying levels of detail in the published literature that we discuss here and outline in Table 1, previous efforts have ranged from simple taxonomic lists to detailed examinations of quantitative and morphometric aspects of archeofauna. Although it must be conceded that some data is better than none, the lack of detail hampers our ability to discuss subsistence strategies with any degree of confidence. Archeologists should be exhorted to collect faunal remains consistently across a site and attention must be directed towards smaller fauna, including fish, and elements that are typically overlooked when screening processes are not used. Because we recognize the salvage conditions that obtain throughout much of Chinese archeology, and the general paucity of zooarcheologists to examine the collected remains, we propose that sampling strategies need to be more thoughtfully and uniformly applied to Chinese field methods in order to allow for the sorts of collections that can be used confidently in this research. The logic of sampling is not currently an intuitive part of the paradigm within which most of Chinese archeology is practiced, but without consistently collected samples, all of the results of quantitative approaches to domestication discussed at the beginning of this paper are suspect. Archeologists generally need to insist on systematic collection strategies if quantitative data are to be relied on at all. This recommendation applies not just to zooarcheology but also to ceramic studies – the bread-and-butter of Chinese archeology in the "quxi leixing" 區系類型 tradition. It should be made clear that this is not a problem unique to Chinese archeology. Despite the much longer tradition of sampling and quantitative analysis in archeology practiced in the Western tradition, a high degree of variability remains in collection strategies. That said, this should not be seen as an excuse for not adopting more consistent techniques in China. The employment of consistent collection and sampling strategies will allow for much more thorough analyses of material culture in the future.

Among the issues that could be more thoroughly discussed with systematically collected data is the question of animal exploitation in the Northwest regions of China during the Neolithic. The current evidence, as discussed above, suggests several general patterns. Most important among general patterns is the role that the Hexi Corridor in particular seems to play as a route of interregional communication as early as the Neolithic. One line of evidence for this communication is the chronological patterns in domesticated animal use. For example, Qijia Culture sites in this region provide some of the earliest, albeit equivocal evidence of horse use in China. If Qijia people were, in fact, using horses as pack, transportation, or even traction animals, this would have greatly increased the area in which communities sharing some aspects of material culture may have been in regular and direct contact with one another. The inclusion of sheep in Qijia assemblages further supports the notion that Qijia communities were connected, in some way, to populations further afield who exploited animals not previously seen in this part of Asia. Based on these animals, it might be hypothesized that some form of mounted pastoralism had already emerged by this point, but such a conclusion should not be considered inevitable and much more work needs to be done on this question.

In fact, Northwest China was a recipient of different types of domesticates from various directions. As mentioned, sheep and horse almost certainly were introduced from the north and west, probably through the Hexi Corridor itself. Camel may have been domesticated nearby, perhaps in the Ordos region or, alternatively, also were an introduction from Central Asia. Pig and dog, which are common in Northwest assemblages, were almost certainly introduced from places further to the east. As for cattle, the jury may still be out as to which neighboring region was most responsible for their introduction into the Hexi Corridor and adjacent regions. This potpourri of domesticates suggests processes of introduction that are not straightforward. Although the picture painted here clearly implicates "diffusion" in the process, the lamentation by Colin Renfrew 35 years ago that the process of diffusion is rarely explained can be applied here (1970: 208). To repeat a related, yet cogent statement concerning this issue, "the diffusion of the quite limited and unrepresentative congeries of artifacts and materials surviving for the archeologist to recognize is merely one end product of complex patterns of interaction, almost all of them involving reciprocal exchange and almost all of them proceeding simultaneously on many levels" (Adams 1974: 241). There were almost certainly population movements in Northwest China during the Qijia period, but clearly more complicated processes were involved in the introduction of a variety of domesticated animals into this region than straightforward demic diffusion from a single direction. Populations existed in the Hexi Corridor prior to the Qijia culture, most prominently associated with the Majiayao tradition, and this zone was already an important pathway between regions from deep antiquity.

Considering this fact, and the currently available evidence related to the timing of the introduction of animal domesticates, it seems that the shift to a focus on domesticated animals was part of a complicated process of cultural change, population contact, and migration. When domesticates such as dogs, pigs, cattle, sheep, and horse were introduced to the region they already were part of symbiotic relationships with humans, and whereas climatic changes may have been a stimulus for some of this diachronic change, there is no a priori reason to suspect that environmental circumstances catalyzed a shift towards increasing reliance on domesticates. As further research on populations and climate become available in this region, we will be able to assess this relationship more clearly.

The summary we have provided here is clearly only a beginning. There are many holes to be filled, and this can only happen if more attention is paid to faunal assemblages during the excavation of sites in this important region. In addition, the summary has highlighted the fact that the circumstances of human activity in the Hexi Corridor prior to 4.0 ka are completely unclear. Attention should be focused on this lacuna in our understanding, particularly if we are to understand the role that the area historically known as the "silk road" played in inter-regional communication during the Neolithic period.

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Yaks, yak dung, and prehistoric human habitation of the Tibetan Plateau

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Abstract

This paper explores the importance of yak dung as a source of fuel for early human inhabitants of the Tibetan Plateau. The wild and domestic yak is introduced, followed by a discussion of yak dung production, collection, and energetic return. Yak dung is compared with other products such as milk, pack energy, and meat, demonstrating its high energetic value while emphasizing that various yak products serve different, complementary, and nonfungible purposes. Following this review of yak dung energetics, issues related to the early peopling of the Tibetan Plateau become the paper's focus. Availability of yak dung as a fuel was a potentially critical factor for colonization of the high Plateau, where other fuel sources are largely lacking. The patchy distribution of dung on the landscape may have required the development of various strategies for ensuring an adequate supply during foragers' travels in the high Plateau. Meeting fuel needs may have led to the integration of the wild yak into human settlement systems and may have contributed to behaviors that resulted in the yak's domestication.

> "No yak, no Tibetan people."
> Lobsang Trinley Lhundrup Choekyi Gyaltsen
> 10th Panchen Lama (Wu and Wu 2004)

1. Introduction

People living on the Tibetan Plateau rely for survival upon the yak, the region's native cattle. The yak is the load-packer for pastoralists on the move in the Plateau's high pastures and the wagon- or plow-hauler for farmers on the fringes. Yaks give daily sustenance in the form of milk, butter and cheese, yoghurt and whey, and occasionally meat and blood and fat. The long strong outer hairs of the yak's coat furnish ropes, tent cloth, pack bags, and ornamentation (Hollywood has lately discovered what Tibetan women have long known, that they are ideal human hair extenders). The yak's fine wooly underfur is made into yarn, felt, clothing, and blankets. Yak leather goes into bags, belts, boots, bundles, binding, bridles, bellows, boat hulls, breastplates, and beyond. Pastoralists trade yaks and yak products with neighboring farmers, merchants, and lamaseries for the essentials and luxuries not available locally – tea and oil, barley and peas, spices and snuff, pots and pans, tea bowls and prayer wheels, tent poles and needles, silk brocade and silver plate, rifles and binoculars. In the spiritual realm, the yak is godly, its skulls and horns and butter fashioned into icons to be revered. Yak butter keeps firelight alive in lamps religious and secular.

More prosaically, yak dung serves nearly all heating and cooking needs in a land where people require ample fuel but where wood or coal are scarce or nonexistent. Traditional Tibetan pastoral economy is fueled mainly by dung of yak, sheep, and goat (Goldstein and Beall, 1990). Each year, the yak produces three to four times its own weight in dung, a load that goes into cooking and heating, plaster and manure, construction of fences, walls, shrines, and storage rooms and is sometimes traded or sold to obtain other needed commodities. Over the course of its life, the typical domestic yak yields a greater potential energetic contribution through its dung than through milk, transport energy, or meat. Resident Tibetan and Mongol pastoralists have relied on yak dung for several thousand years, and Paleolithic hunters striving to live in the Tibetan high country before pastoralism probably also depended on yak dung. Indeed, one may speculate that the yak's domestication was initiated and sustained as much by people's need for dung fuel as by the use of other products such as meat, hair, or hide; and that other benefits of yak domestication, such as pack energy and milk, must have come as secondary benefits later in the process. To know how people settled in the inhospitable Tibetan Plateau as hunters or pastoralists, it behooves us to understand the energetics of yak dung.

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2. The Yak (*Bos [Poephagus] grunniens*)

Phylogenetically the yak is grouped with the Bovini, closely related to wild cattle and bison, but its nearest congener is not clear: some place it with *Bos* (Groves, 1981; Ritz *et al.*, 2000), others *Bison* (Geraads, 1992; Verkaar *et al.*, 2004; Lai *et al.*, 2004). The yak is typically considered a subgenus of *Bos* (e.g., Wilson and Reeder, 1993; Nowak, 1999), but anatomical and genetic differences may justify its separation into its own genus *Poephagus* (cf. Olsen, 1990; Olsen, 1991; Wiener *et al.*, 2003, p. 18; Han, 2003, p. 432). Genetic evidence suggests the yak diverged from other cattle lineages 1–2 million years ago (Tu *et al.*, 2002), as the Tibetan Plateau was rising in elevation.

2.1 Wild Yak

The wild yak reigns in alpine habitats of the high Tibetan Plateau above 3000 m altitude, where other cattle fare poorly. Wild yaks were widespread and abundant in the Plateau and other high mountain ranges in central Asia before modern hunters decimated their numbers in the late twentieth century (Hoffmann, 1991; Lu, 2000). Currently, wild yaks are highly endangered with an estimated population of 15,000 or less, restricted to the remote Changtang region of the northern Tibetan Plateau and the Qilian Mountains (Schaller and Wulin, 1995; Schaller, 1998; Lu, 2000). Wild yaks are protected by law but still illegally hunted and their numbers appear to be declining overall, though populations in some protected areas have recently been on the rise (Harris and Loggers, 2004).

Wild yaks are massive, with great black upward- and backward-curving horns and long shaggy black to brown pelage covering the body including the tail. Pronounced sexual dimorphism characterizes the wild species. Adult males (called *drong* or *aBrong* in Tibetan) can be 2 m high, over 3 m long, and typically weigh 600 to as much as 1200 kg (Lu, 2000), while females (*dri* or *aBri*) are considerably smaller, weighing only 300 kg on average. Compared to domestic cattle, yaks possess large lungs and heart, a short wide trachea permitting rapid respiration, expansive sinuses, high hemoglobin concentration and red blood cell count, thick fur, and few sweat glands, all adaptations to the low level of oxygen, high solar radiation, and extreme cold of their high-altitude homeland.

Two wild ecotypes are recognized (Lu, 2000). One, called *Gaxi* by Tibetans, is restricted to alpine meadows in the western Qilian Shan and Aerjin Shan mountains. The *Gaxi* is a relatively gracile form, bulls weighing up to 600 kg and reaching 170 cm height at withers with 210 cm chest girth. The *Gaxi* possesses a prominent shoulder hump, long legs, long face, small muzzle, short ears, no dewlap, a fluffy broom-like tail, and horns curving gracefully backward. Pelage is brown-black with a gray nose, eye ring, and back line. These beasts are timid and do not aggressively attack people or other animals.

The other ecotype is the Kunlun yak (called *Hengde*, or "snow hill wild cattle"), found on alpine meadows in the upper reaches of Yaluzangbu River, the Kunlun Mountains, and across the Changtang in northern Tibet. These yaks are much larger than the *Gaxi* type, bulls ranging up to 1200 kg and reaching 205 cm height at the withers with a 270 cm chest girth. The head is massive, with horns having a basal circumference greater than 50 cm (nomads use them as containers to store milk or home-brewed barley beer). The shoulder has a prominent tuberous projection, legs are stocky, and the face is short with a wide expressive forehead marked with gray-white nose and eye rings. Pelage is black to black-brown with grayish back line; the hair is long on the top of the head as well on the shoulder, belly, and legs, long enough to nearly sweep the ground. Kunlun yaks are wary and usually flee at first sight of people, but if cornered or surprised at close quarters (or if they are shot), they may become very aggressive and are widely known to attack people, animals, and occasionally land rovers (Wellby, 1898; Schaller, 1998). The Swedish explorer Sven Hedin noted that yaks and other large game which lived in remote areas not usually inhabited by hunters or herders, were unafraid of people (Hedin, 1905, pp. 469, 478, 501).

Yaks graze on alpine sedges, grasses, forbs, lichens, and mosses. Their specialized tongues, covered with small thorny tubercles, allow them to easily lick up low-lying forage (Schaller and Wulin, 1995). Forage in the high country flourishes from mid-May to late August, followed by a long winter during which time yaks resort to wilted or dead herbage, a period of starvation that may result in 25–30% loss of body mass and frequent deaths (Long *et al.*, 1999).

Yaks form separate male and female groups most of the year, bulls remaining solitary or forming groups up to 10–12 individuals. Females, calves, and some young males herd up from a dozen to two hundred. During the breeding season in late summer and early fall, bulls join the female herds and compete for mates, often violently. Females typically calve beginning at 4–5 years and every other year thereafter, giving birth in early summer. Wild yaks may live to 25 years, but their reproductive span is thought to be about 15 years.

The seasonal foraging movements of wild yaks are not well documented and may vary from region to region depending on local availability of forage, seasonal temperature, and presence of hunters or herders. Yaks may begin the summer growing season in lower elevation valleys, meadows, and Plateau plains, taking advantage of the early-season pastures there, but as summer warms up, they move to developing late-season pastures near snowline and on higher mountains. During winter, they may drop down to lower elevations or remain in the higher mountains. Yaks are well insulated and tolerate cold temperatures better than summer heat, and their movements reflect this preference.

2.2 Domestic Yak

Wild yaks are presently critically endangered, but their domestic descendants (Fig. 1) are abundant in central highland Asia. Some 14–15 million domestic yaks serve as

*Fig. 1. Typical domestic yak (*Bos *or* Poephagus grunniens*), Qinghai Province, China.*

major herd animals through much of the Tibetan Plateau and neighboring Qinghai, Sichuan, and Gansu provinces in China, in bordering highland countries such as Nepal, India, Bhutan, Mongolia, and Russia, and in much smaller numbers in Europe and North America. Domestic yaks differ from the wild stock in size, temperament, and coloration, the domestic varieties often showing white or piebald coats and lacking the gray-white muzzle hairs characteristic of the wild yak. The domestic yak is about 1.5 m tall, with males ranging from 300 to 500 kg weight and females between 200 and 300 kg (Buchholtz, 1990; Wiener *et al.*, 2003). It shares with its wild ancestor many of the physiological and anatomical traits that adapt yaks so well to the cold and harsh environments of the Plateau (Zhang, 2000a). There are two main types, the Qinghai-Tibetan Plateau ("Plateau" or "grassland") type common to the broad meadows and steppes of the Tibetan Plateau and the so-called Henduan or Alpine type of the montane valleys primarily in western Sichuan and Gansu, each with several locally recognized "breeds" (Cai, 1989; Wiener *et al.*, 2003, p. 17; Lai *et al.*, 2004; Zhong *et al.*, 2004). A rich literature on domestic yak production focuses on growth performance, milk yield, hair output, and other measures of productivity of different breeds (see Wiener *et al.*, 2003, for an encyclopedic summary).

Wild and domestic yaks can easily interbreed, though such interbreeding usually does not occur in nature because the two species rarely comingle. In certain situations where wild and domestic yak herds do comingle, solitary wild bulls are sometimes observed hanging around the domestic herds (Lu, 2000), and domestic females sometimes wander off with the wild herds (Harris and Loggers, 2004). In some cases, herdsmen deliberately attempt to cross their females with wild bulls (Weiner *et al.*, 2003, p. 45). On the other hand, wild bulls have been reported to occasionally attack and even kill domestic yak (Buchholtz, 1990). Crossbreeds tend to be larger, fiercer, and more intractable, but they are often preferred by herdsmen for their better growth and more protective nature (Wiener *et al.*, 2003, p. 11). Domestic yaks and cattle also crossbreed, but the male progeny are sterile and subsequent backcrosses are genetically unstable, so breeding of these crosses typically stops at the first generation (Wu, 1998; Weiner *et al.*, 2003, pp. 33–59). These yak–cattle hybrids, called *dzo* in Tibetan and *pian niu* (犏牛) in Chinese, are highly regarded by herders and farmers at the lower elevation range of the yak. The *dzo* are larger, produce more milk, work as pack or draught animals better than purebred yak, and are well suited to an elevation niche between the upper limit of cattle and the lower limit of the purebred yak, roughly 2500–3500 m.

2.3 Yak Domestication

As to the domestication history of the yak, very little is known (see Flad *et al.*, this volume; Palmieri, 1976; Clutton-Brock, 1981; Olsen, 1990). According to Zeng and Chen (1980), yaks were originally hunted on the Tibetan Plateau and in mountains of Shangxi and Hubei Provinces in China, until they were tamed and domesticated by the Qiang people. The Qiang (羌, a term meaning "shepherds;" Lattimore, 1940, p. 215) refers to non-Han ethnic groups inhabiting the Tibetan borderlands in Sichuan, Gansu, and Qinghai Provinces, including the Qinghai Lake area (Hoffman, 1990). "It is believed that the yak was tamed and domesticated by the ancient people of Qiang (the supposed ancestors of the tribes of Tibetan, Qiang, Yi, and Naxi) in Changtang of northern Tibet about 5000 years ago (during the Longshan Culture period)," note Wu and Wu (2004).

> Since then, the yak and the ancient Qiang people coexisted and the yak became a sign and totem of the tribes, and was used to name the tribes or places. It is recorded that a clan of the Qiang people once migrated south to Kangding of Ganzi in western Sichuan and established the historically famous country, "the Yak State", during the Han Dynasty. A number of different clans like "the yak Qiang" or "the yak clan" was recorded in the historical literatures of the Han Dynasty. They were engaged in the yak keeping, the area where they stayed was administratively called "the yak country," and the mountain and the river where their yak grazed and drank was named as "the yak mountain or the yak river" (Wu and Wu, 2004).

Trade routes involving domestic yak were recorded as early as the dynasties of Qin (221–206 BC) and Han (206 BC to AD 220), and crossing of yaks with Chinese yellow cattle to create the hybrid *dzo* is described in ancient writings (Zeng and Chen, 1980). Zhang (2000b) notes that "systematic crossing of yak with other cattle has been recommended and practiced for many years; ancient documents indicate that yak have been crossed with common cattle (*Bos taurus*) for at least 3000 years. Documents from eleventh century China (Zhou Dynasty [1040–771 BC]) suggest that crossing of yak with cattle by the Qiang people gave benefits now recognized as heterosis. From the earliest times, the name 'Pian Niu' (and other variants) has been used to describe these hybrids. These crosses find a special niche with herdsmen, usually at a somewhat lower altitude than typical yak country. Crossbred females are an important source of milk and dairy products. Since males cannot be used for breeding, they are used as draught animals or are slaughtered for meat. These hybrids are very suitable for work as they are easily tamed and have better heat tolerance than pure yak."

Bailey *et al.* (2002) examined mitochondrial DNA from domestic yaks in Bhutan, Nepal, China, and Mongolia to identify two distinct haplogroups, hypothesizing that yak domestication occurred twice, similar to other cattle (Loftus *et al.*, 1994) and other ungulates (Bradley, 2000). Bailey and her colleagues used a "molecular clock" estimate to suggest that divergence from the wild stock took place about 5000 years ago, cautioning about a wide latitude for error. This estimate corresponds generally with limited available archeological and historical records (Olsen, 1990; Flad *et al.*, this volume).

3. Importance of Yak Dung

Dung of various herbivores, called *argol* from the Mongol word for "animal droppings," is widely used as fuel in central Asia, just as it is in other parts of the world lacking adequate supplies of wood (see, e.g., Winterhalder *et al.*, 1974; Wright, 1992). The importance of dung fuel in central Asia was recognized by the nineteenth-century Lazarist missionary Abbé Evariste-Régis Huc (1898, pp. 89–90) whose pioneering survey, brief as it is, deserves reiteration for a modern audience:

> The luxurious variety of combustibles which the civilized nations of Europe enjoy, have exempted us from the necessity of making very profound researches into the divers qualities of argols. Such has not been the case with the shepherd and nomadic peoples. Long experience has enabled them to classify argols, with a perspicuity of appreciation which leaves nothing to be desired in that particular respect. They have established four grand divisions, to which future generations will scarcely be able to apply any modification.
>
> In the first rank are placed the argols of goats and sheep; a glutinous substance that enters largely into its composition, communicated to this combustible an elevation of temperature that is truly astonishing. The Thibetans and Tartars use it in the preparation of metals; a bar of iron, placed in a fire of these argols, is soon brought to white heat. The residuum deposited by the argols of goats and sheep after combustion, is a sort of green vitreous matter, transparent, and brittle as glass, which forms a mass full of cavities and very light; in many respects, closely resembling pumice stone. You don't find in this residuum any ash whatever, unless the combustion has been mixed with foreign matter. The argols of camels constitute the second class; they burn easily, and throw out a fine flame, but the heat they communicate is less vivid and less intense than that given by the preceding. The reason of this difference is, that they contain in combination a smaller proportion of glutinous substance. The third class comprehends the argols appertaining to the bovine species; these, when thoroughly dry, burn readily, and produce no smoke whatever. This is almost the only fuel you find in Tartary and Thibet. Last come the argols of horses and other animals of that family. These argols not having, like the others, undergone the process of rumination, present nothing but a mass of straw more or less triturated; they throw out a great smoke when burning, and are almost immediately consumed. They are useful, however, for lighting a fire, filling the office of tinder and paper to the other combustibles.
>
> We perfectly understand that this rapid and incomplete essay on argols is not of a character to interest many readers; but we did not feel justified in either omitting or abridging it, because it has been an object with us to neglect no document that might be of assistance to those who, after us, might venture upon nomadic life for awhile.

Huc's appreciative and absorbing account contains very little concerning "argols appertaining to the bovine species …almost the only fuel you find in Tartary and Thibet." Wild yak fecal productivity and use are equally poorly measured by modern science. Dung production of the domestic yak may help to illustrate the productivity and utility of the dung of its wild ancestors, given proper allometric and environmental allowances.

3.1 Dung Production

The amount of dung produced by a yak is a function of feed intake and quality of diet, which vary with season and grazing conditions, as well as animal size. Long (2003a, p. 391) notes that an adult grazing yak will consume "18–25 kg fresh forage in summer to 6 to 8 kg per day, or even much less, of wilted grass in cold-season grazing conditions." These are fresh forage values; dry matter (DM) intake is a preferable measure for assessing dung fuel production since moisture content can vary so much and since dung fuel is burned dry. On a DM basis, an adult yak will consume "4–5 kg DM per day in summer and autumn, and be reduced to 1–1.5 kg DM per day, or even less, during late winter and early spring" (Long, 2003b, p. 369). During the summer "the energy and protein intakes are adequate to meet maintenance, work and production, but in the later parts of the winter and early spring they fall below the requirements. Yak then lose weight and condition" (Wiener *et al.*, 2003, p. 80).

Liu *et al.* (1997, cited in Long, 2003a) report that a 2-year-old yak consumes 3.4% of its body weight in DM each day under premature summer grazing conditions and 3.0% in mature growing period conditions; 3-year-olds consumed slightly more, 3.9 and 3.5%, respectively. Chen *et al.* (1994) report a slightly lower figure, ~3.16 kg DM per 100 kg body mass each day. Of this amount, 69.7% is digestible, meaning that 30.3% (0.96 kg per 100 kg body mass) is nondigestible DM that is excreted as feces.

If an amount of DM equaling ~3.5% of body weight is consumed per day and ~30% of that DM is excreted as feces, then ~1.6% of body weight is excreted as feces per day. If these proportions apply to wild stock, then a 500 kg bullock may eat 17.5 kg DM per day and yield as feces 5.25 kg DM per day, ~1916 kg per year, about 3.8 times its body mass. Obviously, a really big bull of 1000 kg will produce much more. The smaller wild cow, at 300 kg, leaves about 3.1 kg per day and 1150 kg per year.

The quality of forage has an important influence on the amount of dung produced. Summer range forage digestibility may range 65–70% (Cincotta *et al.*, 1991), but is often less than 50% especially during the long winter and spring "starvation" months. If in winter a yak eats only 2 kg of standing dead forage per 100 kg body weight per day, with an average digestibility of 50%, then a 500 kg bullock would deposit 5 kg of dry weight dung each day and a 300 kg cow would leave 3 kg each day or about 3.65 times their body weight if computed on an annualized basis. Schaefer *et al.* (1978) used experimental conditions with controlled feed at a digestibility of 49.3%, and obtained essentially similar values, ~3.5 times body weight per year.

This prodigious amount of dung turns out to yield a considerable amount of energy. We measured caloric fuel content of dung of domestic yaks and other main domestic herbivores common in central Asia (Table 1). Samples were collected in the Qaidam Basin, gathered in the field, so no information is available about the diet of the participant animals; dung fuel content of animals on different diets and during different seasons merits further study.

By weight, the gross caloric values of dung from different animals are quite similar, probably reflecting a similar grass and herb diet (the camel sample may reflect a greater proportion of browse). By volume, however, the samples vary considerably in caloric value as a function of density and particle size. These structural differences, the result of distinctive digestive processes, account for the variation in fuel behavior noted by Abbé Huc and others. Sheep, yaks, and camels are ruminants, with a multichambered foregut to facilitate fermentation and breakdown of cellulose. Sheep and goat dung is dense and composed of very finely divided particles of organic matter, while yak dung is less finely divided and more open in structure. Horses are hindgut digesters, with an enlarged cecum and colon to process large amounts of low-quality fibrous feed, and their dung is very coarse. Variation in feces particle size probably has as much significance for its utility as fuel as it does for understanding the feeding ecology of different herbivores (Clauss *et al.*, 2002).

Our specific results indicate that yak dung yields about 3307 kcal of heat energy per kg or about 900 kcal per liter of dried dung flakes. By way of comparison, if a kilogram of yak dung was converted (with perfect efficiency) into electrical energy, it could operate a typical personal computer for 9.6 h or a 60-W light bulb for 2.67 days. A liter of yak dung will bring a liter of ice-cold water to boil at 5000 m if it is burned in a typical cast-iron stove with an energetic efficiency of ca. 9.6% (water boils at 85° C at this altitude). Assuming that yak dung is identical to cow dung in its burning efficiency, it burns in an open fire with ~3–5% efficiency; for reference, wood burns with 5–8% efficiency and contains about twice the heat energy of dung (UNESCO, 1982). A liter of yak dung burning in an open campfire would therefore yield about 27–45 kcal of usable heat for cooking, enough to boil 0.3–0.5 l of ice-cold water.

This heat energy value suggests that a wild yak bullock of 500 kg, having an average feed intake of 3 kg per 100 kg body weight and an average feed digestibility of 50%, resulting in 7.5 kg of dung per day, would yield 24,802 kcal of total fuel energy per day, or some 9 million kcal per year. A female 300-kg yak on the same diet would give 4.5 kg of dung and 14,882 kcal of fecal fuel energy per day, or 5.4 million kcal per year. Depending on technology, 3–10% of this heat would be usable for cooking, with the rest of the energy lost to the immediate environment. This potential heat energy is, of course, scattered in the pasture and around camp and requires collection and processing for use.

3.2 Economics of Yak Dung Collection and Use

Yak dung collection and use was investigated in Qinghai Province, China, where dung fuel remains a critical

Table 1. Energy content of different herbivore dung samples, Qaidam Basin, Qinghai Province, China. Gross energy measured by calorimetric bomb by Atlantic Dairy and Feed Institute, Fredericton, New Brunswick, Canada.

Fuel	Gross energy (kcal/kg)	g/l	kcal/L
Yak	3306.6	270.0	892.8
Sheep	3771.1	236.1	890.4
Camel	3660.4	207.8	760.6
Horse	3634.6	132.7	482.3

Table 2. Daily work calendar of the Madam Cuotou (Age 53) Family, Jianshe Township, Dari County, Qinghai Province, China. Redrawn from Liu et al. 2001, Table 7.4.12.

Hour	Husband		Son	Wife			Daughters
5				Get up		Milk	
6					Pick up Dung		
7	Meal		Herd sheep	Cook and meal			
8		Herd horses, drop in other herds, diagnose animal illnesses, process sheep leather				Process milk	Two daughters herd yak in turn
9						Make cheese	
10					Dry dung	Herd calves and milk	
11	Lunch			Cook and meal			
12					Pick up dung and transport dung		
13							
14							
15							
16	Tea		Rest				
17			Herd sheep				Milk
18	Spare time						Herd yak
19					Gather and store dry dung		
20		Tie down horses					
21	Supper			Supper and to bed			
22	To bed						

commodity among both herders and village dwellers alike. Collection of yak dung may be sustained or sporadic, depending on situation and need. Dung collection is done primarily by women and children, particularly for day-to-day use. Women will typically spend 2–3 h per day collecting and processing dung, but this task may be accomplished while conducting other tasks such as herding (Table 2). Men take part in dung collection on special foraging trips when large quantities are gathered, for commercial ventures, or when they are alone herding. Several situations observed in the field or in the literature are discussed below.

1. An extended Tibetan family of 13 was observed living near the village of Heima He, south of Qinghai Lake, in a typical three-room mud-brick house about 15 m long by 5 m wide. For fuel they relied entirely on *niufen* (牛糞), the Chinese term for yak dung, which they collected themselves. The dung was stored outside the house in large heaps; such heaps can be seen throughout the Tibetan Plateau, next to these permanent houses (Fig. 2). Each heap was roughly 2 m wide, 3–4 m long, and 1 m high, rounded and with a hard dry dung coat to repel rain. A heap took about a month of intermittent work to collect, mainly during autumn. A heap, roughly 8000 l, resulted in about 16,050-l bags of dung. The family used a heap every 2 months in the summer (about 133 l per day), one every month in the winter (about 260 l per day), or about 10 piles per year. The annual total amounts to about 80,000 l of dung, perhaps 22,000 kg total, the output of about 12 yak each contributing 5 kg per day. Energetically,

Fig. 2. Dung piles next to permanent Tibetan home.

this amounts to 6.4 million kcal per year, or about 494,000 kcal per person per year.

2. A group of three adults who lived in a cinder block house in Heima He were observed wheeling a barrow holding six large burlap sacks filled with moist yak dung they had just collected from nearby pastures. Each sack, carrying an estimated 350 l, could be filled in about 10 min. One member of the group said that each bag lasted about 10 days (about 35 l per day), for cooking and heating needs. This group thus spent a couple hours of collection time to gather about 2 months' fuel supply (travel included, but processing time for drying the wet dung is extra). Thirty-five liters per day is considerably less use than the previous case, and it is not known what other fuel sources were available to this small family. However, the time spent in collecting dung was apparently well rewarded and not a limiting factor to its use. If a full day's work was spent in drying the dung and the volume decreased by 50% (both conservative guesses), then a caloric return of about 950,000 kcal in ~15 h would be the result, or about 63,000 kcal per hour.

3. A woman herder living in a tent camp during the rainy summer season collected the night's crop of yak dung in the early morning after milking, spreading it on the ground to dry it in mid-morning (Fig. 3). She raked up the dried flakes before the afternoon rains and stored it in rice bags for the next day's fuel (Liu *et al.*, 2001). Two to three such bags, each holding about 60 l of dung flakes, sufficed for the day's heating and cooking needs. Therefore, daily summer fuel use in a cloth or hair tent with an earthen firebox amounted to 120–180 l of dung. This amount of fuel is somewhat higher than the first case described above, possibly because the tent she and her family lived in was more poorly insulated than the substantial house of the first group. At roughly 900 kcal per liter, fuel use amounts to 108,000–162,000 kcal per day in the summer. Given approximately 2 h per day the woman spent in collecting and processing dung, she obtained roughly 54,000–82,000 kcal of fecal energy per hour.

Fig. 3. Drying yak dung for daily fuel.

Fig. 4. Hui dung collector, Qinghai Province.

4. A group of Hui dung collectors who lived in a farming village near the Yellow River brought two small trucks to a well-used highland pasture 50 km away. They made this trip a few times each year to collect yak dung in any open pasture, supplementing coal and wood supplies for the winter. One young man collected dung by himself, carrying on his back a loose conical wicker basket (53 cm deep and 62 cm in diameter) that held approximately 75 l. Walking around the pasture, the young man found a moderately dry, collectable dung patty every few paces and flipped it into the basket using a wooden pitchfork (Fig. 4). He gathered 65 such patties in 13 min, until the basket was loosely filled, then he returned to dump the basket into the truck; total time for each collecting bout was about 20 min. (Three or four such baskets, properly dried, would be a day's fuel use in a summer tent camp as depicted in case 3, above.) A second dung-collecting pair consisted of a young woman with a large basket on her back (~145 l), into which an older man shoveled wet dung patties. Another man stood in the truck and packed down the basket loads as they came in.

Each truck carried approximately 1800 l, or about eight of each of the large and the small basket loads, but the dung in the truck was packed more tightly than in the basket, so each truckload probably counted for 12 of each basket load. Assuming 20 min per collecting bout, each truckload could be gathered in 4 h of work by the four collectors. By the time we had met this group, they had already worked 4 h and had one truck filled (Fig. 5). Thus, one good day's work would supply several months' worth of fuel, though fuel still required processing and drying.

Again, the limiting factor in dung fuel use does not seem to be abundance or the time spent in collecting, at least in pastures well used by domestic yak herds. The most time-consuming effort is probably involved in drying and processing. Nevertheless, yak dung appears to have been sufficiently economical a fuel to warrant special collecting trips from at least 50 km away. Though this group indicated

Fig. 5. A large load of fuel collected by four people in 4 h.

the dung would be used for fuel, it could also have been gathered to fertilize gardens or fields, if the farmer lacked other manure sources for that purpose.

5. A Mongol herdsman lived with another herder in a small camp near Xidatan, not far from Kunlun Pass, in Qinghai Province (Fig. 6). The young men occupied a canvas wall tent about 4 × 5 m in dimensions, with a small cast-iron stove for heating and cooking (Fig. 7). He used about 8 l of dry crumbled yak dung flakes to stoke a fire sufficient to boil one or two large kettles of water, about a liter of fuel for every liter of water boiled. This he would do two or three times a day, during meals. He collected from around the camp whenever he needed fuel and kept no more than a few days' supply stored up, at least while we were there in the summer. He said that in the winter he used about 30–40 l of dung each day to keep warm and cook. He mainly used yak dung, but sometimes he added sheep dung as well because it burned hotter. A bit of rubber from a tire tube worked the same. In all, if he used a base amount of ~24 l of dung per day for meals and an additional ~12 l for warmth in the cold months (October–May), this herdsman in his small canvas tent would need about 11,700 l (3160 kg) of dung each year. Assuming that this man's estimate is correct, and given the small size of his domicile and the bitter cold of a Tibetan winter, this daily amount of fuel appears surprisingly small; it suggests that the fuel is used mainly for cooking rather than maintaining a comfortable indoor air temperature, as noted by other investigators (Goldstein and Beall, 1990).

Fig. 6. Mongol herdsman in tent, near Xidatan, Kunlun Pass area, Qinghai Province.

Fig. 7. A small cast-iron stove fueled with dung serves all heating and cooking needs.

6. An additional interesting case was provided in 1852 by Abbé Huc (Huc, 1898, p. 89). He wrote:

> We observed, also, flocking to Tchogortan, another class of Lamas not less interesting than the Mongols; they always arrived at daybreak; their garments were tucked up to the knees, and on their backs were large osier baskets; all day long they would traverse the valley and the adjacent hills, collecting, not strawberries and mushrooms, but the dung which the herds of the Si-Fan [yak] deposit in all directions. On account of this particular occupation, we named these Lamas Lama-Argoleers, from the Tartar word argol, which designates animal excrement, when dried and prepared for fuel. The Lamas who carry on this class of business, are in general idle, irregular persons, who prefer vagabondizing about on the hills to study and retirement; they are divided into several companies, each working under the direction of a

> superintendent, who arranges and is responsible for their operations. Toward the close of the day, each man brings the portion he has collected to the general depot, which is always situated at the foot of some well, or in the hollow of some valley. There the raw material is carefully elaborated; it is pounded and molded into cakes, which are placed to dry in the sun, and when completely desiccated, are symmetrically piled, one on the other, the stack, when formed, being covered with a thick layer of dung, to protect it from the dissolving action of the rain. In the winter, this fuel is conveyed to Kounboun, and there sold.

7. One final case, from Waddell (1906, p. 103), illustrates the value placed on stores of yak dung by Tibetan communities and their colonial antagonists:

> A curious illustration of the monetary value of fuel in this arctic region, where the only available material, namely, yak-dung, is a life necessity, came to light, when, owing to our telegraph wire having been cut near Phari, a fine was inflicted on the town of dried yak-dung fuel, as this was badly required by our troops. A fine of fifteen tonnes of cakes of this material was imposed, which at local barter rates represented in money about L15 sterling. So effectual was the fine, in this local coinage of the country, that they willingly paid half of it in Indian rupees, to escape parting with this invaluable article, and the line was never cut again. Without this commodity all human life in this barren part of Tibet would be impossible. As it is, the Tibetans seldom warm themselves at fires, but trust to thick clothing and animal food to keep themselves warm, and use fuel only for cooking. The yak are indeed a godsend in these barren regions. They are never given any food by their owners, but are sent adrift to forage for themselves, yet in return they work as beasts of burden, give milk for butter, and their own flesh for food, and also bestow the indispensable fuel daily. This arrangement recalls the extensive use of a similar article for the same purpose in India, where firewood is scarce, and where its substitute is gratefully called by the Indian peasantry "the gift of the cow" (go-bar).

These few cases, mixing anecdotal evidence and fairly rough measures of time spent in collecting dung, the amount of dung used for various cooking and heating purposes, and the caloric return of the dung utilized, highlight four main points. Most important, a modest amount of time expended in dung collection can result in a very substantial return of fuel, sufficient for all cooking and (in many cases) significant heating needs. In places where yaks graze, the availability of dung is not a limiting factor in collection. However, the amount of time and effort needed to dry and process enough dung to maintain a sufficient daily store in the rainy summer season may be a limiting factor in dung use. Finally, considerable variation in the use rates of dung fuel is notable in these few cases, probably reflecting situational flexibility. More detailed investigations of dung collection and use rates are warranted to further explore the energetics of this traditionally important fuel source.

4. Energy of Other Yak Products

Dung is just one product among many. It is worthwhile to compare its energy value with some of the yak's other contributions.

4.1 Milk

Milk and milk products are among the most important contributions of domestic yak. As Wiener *et al.* (2003, p. 136) note, "milk yield is closely related to pasture growth and quality and, in general terms, the amount of milk produced by the yak cow is considered as no more than the amount needed for the normal growth and development of its calf. In this respect, the milk yield of yak is more akin to that of animals in the wild than to the milk yield of dairy cattle." Yak cows typically have a lactation period of 150–180 days, with average daily yield ranging from 1 to 3 kg (Wiener *et al.*, 2003, p. 138), depending on breed, condition, whether the cow has calved (which typically occurs every other year), milking strategy (e.g., once or twice daily), and time of year. Milking twice daily can increase yield by about one-third. Yak–cattle hybrids, or yak cows that were the progeny of wild yak–domestic yak crosses, may produce substantially more milk than purebred yak cows.

In general, a purebred yak cow of the Plateau type can be expected to produce an annual yield of 150–250 kg of milk. The milk is dense and sweetish, about as rich as ewe's milk and richer than a dairy cow's, with 15–18% milk solids, fat content averaging about 5.5–7.0%, protein and lactose approximately 4–5.5% each, and total energy about 850–1000 kcal per kg (Wiener *et al.*, 2003, p. 148). If a yak cow produces 200 kg annually, she may yield up to 200,000 kcal of milk energy.

By comparison, over the year that same cow can easily produce 1500 kg of dung, resulting in a total dung energy yield of nearly 5 million kcal, some 25 times the energy content of her milk. Of course, milk energy in the bucket is already captured, whereas the dung must be collected; much of the dung, probably most of it, will remain in the pasture to fertilize next year's herbage. More important, yak milk is directly consumed and digested by people, whereas dung is not. Nonetheless, this example indicates the relative magnitude of energy available from dung and milk.

4.2 Pack and Draught Energy

Known as the "ships of the plateau," yaks are highly valued for their sure-footed capabilities in packing large loads over long distances, and they are safer than horses for riding in swampy ground, through rivers, or on steep rocky slopes. Farmers at lower elevations use yaks to plow fields and haul carts or other loads. Steers typically serve as pack and draught animals. Yaks can pack loads of 60–80 kg for 20–30 km per day without difficulty, sometimes for periods exceeding a month (Wiener *et al.*, 2003, pp. 165–167). Loads of over 300 kg (over 85% of body weight) have been carried for shorter distances, at altitudes exceeding 4000 m. A plow weighing 390 kg can be pulled by a yak steer of about the same weight.

A pack yak that carries a load of 70 kg for a distance of 25 km at a rate of 4 km per hour ($=7.78 \times 10^7$ g-cm/s) yields about 0.763 kW of power or about 10.9 kcal per minute. Over the total trip of 6.25 h, the resulting energy outlay is approximately 4100 kcal. If the pack animal makes such a trip 100 days per year, the annual pack energy output would be 410,000 kcal, a very significant and highly valued energetic contribution. For comparison, the same pack yak would leave on the trail about *six times* that amount of energy in the form of burnable dung. The two forms of energy serve very different purposes, however, and are not easily convertible.

4.3 Hides and Hair

These products have an important energetic role, primarily to reduce heat loss to the environment through use as clothing, blankets, tents, and the like. Yak hair, especially down, can make excellent wool with good heat-retention properties, and though the hair has poor felting qualities, it can be combined with sheep or camel hair to create felt. The felt that goes into traditional Tibetan robes and as insulation in yurts and tents is an excellent thermal insulator.

The yield of hair and down varies considerably depending on age, sex, and breed (Wiener *et al.*, 2003, pp. 156–163). Tibetan Plateau breeds yield relatively little, between 0.5 and 2.0 kg per animal per year; other breeds yield between 2 and 4 kg; the very furry male Jiulong yak, bred for its fiber, may yield as much as 25 kg per year (Wiener *et al.*, 2003, p. 157). Down accounts for about 40–50% of the total yield in 2–4-year-olds.

An example of the heat-retention capacity of traditional fiber products can be gleaned from a study of the yurt, the Mongol portable house (Manfield, 2000). Multiple thick layers of felt (mainly sheep and goat) give the yurt its great thermal efficiency: the *R*-value (a measure of resistance to heat flow) of 20 cm of felt is calculated to be 5.12 $W/m^2 \cdot$ C, the equivalent of about 4 cm of fiberglass batting. Total heat flow from the yurt was a low 54 W/m^2 and required a relatively low heat input (4.5 kW) to maintain a comfortable indoor temperature of 15° C when the outside temperature was about 35° C below that. This estimate suggests that a comfortable ambient temperature inside the yurt can be maintained using 4.5 kW every hour or about 3870 kcal per hour. That is equivalent to 1.17 kg or 4.3 l of dung per hour (about 100 l a day), assuming that all heat energy stays within the yurt (which it does not).

The yurt has limited distribution on the Tibetan Plateau, being used mainly by Mongol herders at lower elevations in the Qaidam Basin to the north. Among traditional Tibetan pastoralists, the "black tent" (Manderscheid, 2001) is more common, in part because "the black tent is such an important symbolic marker of nomadic Tibetan cultural ethnic identity that the people are loath to abandon them" (Barfield, 1993, p. 187; see also Ekvall, 1968, pp. 61–65). Barfield notes that while "a Tibetan black tent may seem superficially similar to those found in Arabia or Afghanistan, it is sturdier…its panels are made of woven yak hair rather than goat hair…the resulting cloth has a much tighter weave and provides more insulation than the black tents of the arid zones" (Barfield, 1993, p. 187). Over time the panels become infiltrated with smoke from dung fires until they are essentially waterproof (Manderscheid, 2001). Yak-hair tents are by no means as thermally efficient as the yurt and are often freezing cold inside during the long winter (Goldstein and Beall, 1990), but they do cut the wind and keep the stove's heat close by. The *R*-value for the traditional yak hair 'black tent' apparently has not been measured but can be estimated to range between 0.5 and 1.0 $W/m^2 \cdot$° C.

Traditional clothing was estimated to have a thermal resistance or insulating value of up to about 1.6 clo (Manfield, 2000, p. 13). The clo unit is used to describe clothing's insulating capacity (Gagge *et al.*, 1941) and is $\sim$0.155 $W/m^2 \cdot$ C. One clo is roughly the insulating value of a man's underwear and lightweight business suit, or "a heavy top coat alone." The Tibetan long felt robe is roughly equivalent to a heavy top coat, perhaps slightly heavier. The traditional winter fleece-lined sheepskin robe is much thicker, each one requiring eight to ten tanned sheepskins, weighing up to 15 kg (Ekvall, 1968); it may have a clo value of 3–4, near the practical clo limit.

These figures give some idea of the potential heat-saving value of yak hair, though traditionally most clothing and felt products were made from sheep wool and skin, not yak hair. Yak hair, wool, and especially hides are commodities that can be traded for food or other necessary articles.

4.4 Meat

Despite Buddhist prohibitions against killing, the yak is an important source of meat for herders and their families (see Ekvall, 1968; Palmieri, 1976, pp. 117–130; Goldstein and Beall, 1990; Olsen, 1990, for discussions of this issue). Meat usually comes from castrated steers and sterile male cattle–yak hybrids, surplus males, and females at the end of their milk-producing and reproductive careers (though they can still produce valuable dung!).

Wiener *et al.* (2003, pp. 151–152) report that "live weights at slaughter varied with breed and location (and age at slaughter) from 116–576 kg. Dressing percentages ranged from 40–62 percent." The dressing percentage (carcass weight/live weight) tends to range from about 38% for younger animals to over 50% for animals aged 5 years or more. Eighteen-month-old yak with average live weight of 117.7 kg yielded an average carcass weight of 54.3 kg (46% of live weight) and 42.3 kg of meat (35.9%) (Wiener *et al.*, 2003, p. 152). Goldstein and Beall (1990, p. 82) reported a figure of 80–125 kg of meat from a yak carcass. The meat is finely textured, relatively lean, and very tasty. Protein runs about 23%, fat content is ~2.5–3.5%, and the energy content is about 1200 kcal/kg. Assuming a meat to live weight ratio of 0.36, a 300-kg animal would yield 108 kg of meat or 129,600 kcal of energy. The much larger wild yak might produce two to three times that amount of meat, enough for the needs of several families for a winter.

This meat energy is of course a one-time contribution, bringing to an end the living yak's yield in milk, dung, and hair. Some animals are valued and kept alive for their dung and their meat value is "banked" until needed. In this regard, it is worth noting that the same 300 kg animal would yield the same caloric value through its dung in less than 10 days.

Yet the "same caloric value" is obviously not the same at all. We humans cannot eat and bodily assimilate the caloric value of yak dung. Moreover, yak meat may be scarce, but if yaks live nearby then yak dung will be bounteous. These factors must be considered in weighing the relative importance of different energetic commodities.

4.5 *Offspring*

Calves are obviously another important contribution, both to perpetuate the herd and for sale or trade. Typically, a female yak will produce a calf every 2 years between the ages of four and five until 15 or so, yielding between five and seven offspring in her reproductive career. Yak–cow crosses are especially valuable as objects of sale to farmers. Stevens (1993, p. 149) noted that among the Khumbu Sherpa of Nepal, "the breeding and sale of *nak*-cattle crossbreed calves has historically been so lucrative that it was probably the most important factor in the regional prominence of *nak*," as female yak are named in the local language.

4.6 *Social and Spiritual Energy*

One final source of "energy" is the social importance and spiritual or godly aspect of the yak, particularly its "wild" avatar (Olsen, 1990; Wiener *et al.*, 2003, pp. 12–13; Wu, 2003). This energy cannot be discounted, particularly in considering the yak's long-term interactions with people that resulted in its domestication. Tibetan society is often considered to be a yak culture, and the term often used for yak, *nor*, refers to wealth. The wild yak is widely revered as the embodiment of the spirit force of Tibet. Tibetan religion and folklore is rich in legends about the yak (Cayla, 1976; Olsen, 1990).

In light of the yak's spiritual energy, Palmieri (1976) suggested the yaks may have been domesticated for religious purposes, specifically cult sacrifices: "desire to obtain sacrificial bovines for cult purposes in high-altitude Tibet and the Nepal Himalaya thus may well have motivated man to domesticate the indigenous yak in imitation of common cattle" (Palmieri, 1976, p. 279). Following Simoons's (1968) study of the mithan, an Indian ritual ox, Palmieri suggested that the process of domestication involved convincing wild yaks to trust humans via a salt tie, linking the presumed desires of wild yak for salt with humans' abilities to provide it. Herders commonly feed salt to domestic yak in some areas of Tibet and Nepal, making the animals more docile and tractable; herders may also capture and tame wild yak calves for subsequent breeding with domestic yak (Palmieri, 1976, pp. 280–281). According to this hypothesis, "young wild yak/dri, taken by hunters or agricultural folk, could have been brought back to a settlement, where they were given food and salt to bind them to man. Later, when matured, these 'wild' yak/dri could have been allowed to range freely. Occasionally, man would visit his free-ranging animals both to re-establish the salt-tie and to choose animals for sacrifice." Tibetan folk stories support this hypothesis, where the search for salt transforms cattle into yaks or where salt is used to coax wild yaks into submission. Palmieri noted that such a tie would have been unsuccessful on the Tibetan Plateau, where natural salt lakes and other salt sources are common. He suggested that this salt tie must have occurred off the Plateau, on the southern flank of the Himalaya, where salt was largely absent and people and yaks may have interacted for long periods.

The idea of a salt tie in the connection between people and yaks toward domestication remains speculative, as is the proposed place of domestication of the yak, but the spiritual energy connecting the wild yak and Tibetan people is certainly real (Olsen, 1990). The yak's spiritual energy cannot of course be translated into fuel or food energy, but in the Tibetan spiritual world order, yak energy is "good to think" (Levi-Strauss, 1963).

Increasingly, the wild yak is also an important emblem in biological conservation (Miller *et al.*, 1994; Miller and Schaller, 1997; Schaller, 1998; Harris *et al.*, 1999). Now limited to its last stronghold in the remote Changtang, the wild yak population holds on to survival by virtue of geographic isolation, wariness of people, and the Chinese government's attempts to control illegal poaching, which continues despite strong penalties because some individuals are willing to pay large sums to "bag one." The wild yak now survives as a totem for Tibetan society and for conservation efforts worldwide.

5. Fuel Availability on the Tibetan Plateau

The previous case studies provide evidence for the importance of domestic yak dung as a fuel in modern Tibetan pastoralist society. Energetically, dung ranks high in the potential contributions of the yak, though different yak products (fuel, food, transport, heat conservation, and spiritual power) all play very different and complementary roles in supporting Tibetan people. Yak pastoralists live nearby their herds so they have easy access to abundant dung; the limiting factor to its availability, evidently, is the time it may take to process and dry it, especially in rainy summer months, but a family's needs appear to be rather easily met.

Arguably, hunters and other foragers who first occupied the harsh and wood-less Plateau environment before pastoralists must also have depended on dung as fuel (see Rhode *et al*., 2003, for a similar argument regarding Late Pleistocene settlement of high-latitude western Beringia). Unlike yak pastoralists who bring their fuel producers with them, these foragers may have encountered constraints to dung availability in the places where they hunted and camped. It is worthwhile to consider the availability of wild yak dung on the Plateau, if hunters did not bring with them their own herd of dung providers. This issue is addressed in two ways, considering temporal and spatial variability in the availability of fuels on the high Tibetan Plateau, respectively.

Virtually all of the Tibetan Plateau today is covered with treeless and shrubless meadow, grassland, alpine desert, or cushion-plant vegetation (Kingdon-Ward, 1947; Chang, 1981), hence the importance of yak dung as an essential fuel for pastoralists living there (Fig. 8). Forests and shrublands do occur on the lower margins of the Plateau and in the major river canyons draining the high country along the southeast and southwest margins; a few hills and mountains on the outer edge of the Plateau also support isolated stands of trees (juniper or spruce) or shrub communities in a few places up to ~4500 m altitude. The distribution of trees and shrubs differed in the past, however. Charcoal and pollen records from the Tibetan Plateau and Qinghai Lake basin indicate that trees and shrubs grew more commonly and at higher elevations during the Holocene optimum, 6000–8000 years ago, than they occur at present (Yan *et al*., 1999; Kaiser *et al*., 2006; Ji *et al*., 2005; Kaiser *et al*., 2007). People first made sustained forays into the interior of the high Tibetan Plateau (>4000 m) during this same period, as indicated by archeological evidence (Brantingham *et al*., this volume). Miehe *et al*. (2006) report that anthropogenic deforestation occurred in southern Tibet during the Late Holocene and suggest that the region would today be covered in forest rather than desert pastures, were it not for heavy grazing of sheep and goats. A similar argument can be made for the Late Holocene decline of woody shrubs and trees in the Qinghai Lake basin, on the northeast margin of the Plateau (Liu *et al*., 2002; Ren, 2000; Shen *et al*., 2005), a time when pastoralism probably began to be established in this region. Woody fuels were therefore more widely distributed on the Plateau, and especially along its margins, during the period of earliest sustained human occupation and into the later Holocene. Yet even during the Holocene climatic optimum, most of the vast high-elevation Tibetan Plateau would have lacked such fuels and dung would have been the major, if not only, option for these early human colonists.

The types of fuel used by prehistoric foragers occupying the Tibetan Plateau must be confirmed archeologically. Our work in the mid-elevation (~3200 m) Qinghai Lake Basin indicates that local trees and shrubs (*Populus* and possibly *Potentilla*) were commonly utilized for fuel in Late Upper Paleolithic and Epipaleolithic sites dating before 9000 Cal yr BP (Madsen *et al*., 2006; Rhode *et al*., 2007). Dung was apparently used for fuel at one site (Heimahe 3) as revealed by charcoal and ash analysis (Rhode *et al*., 2007; cf. Miller, 1984; Canti, 1997; Hastorf and Wright, 1998). At present, we have no information about the types of fuel sources used by early foragers on the high Plateau.

Spatial variation in the availability of yak dung across the Plateau landscape can be examined via records of various adventurers, religious sojourners, and soldiers who

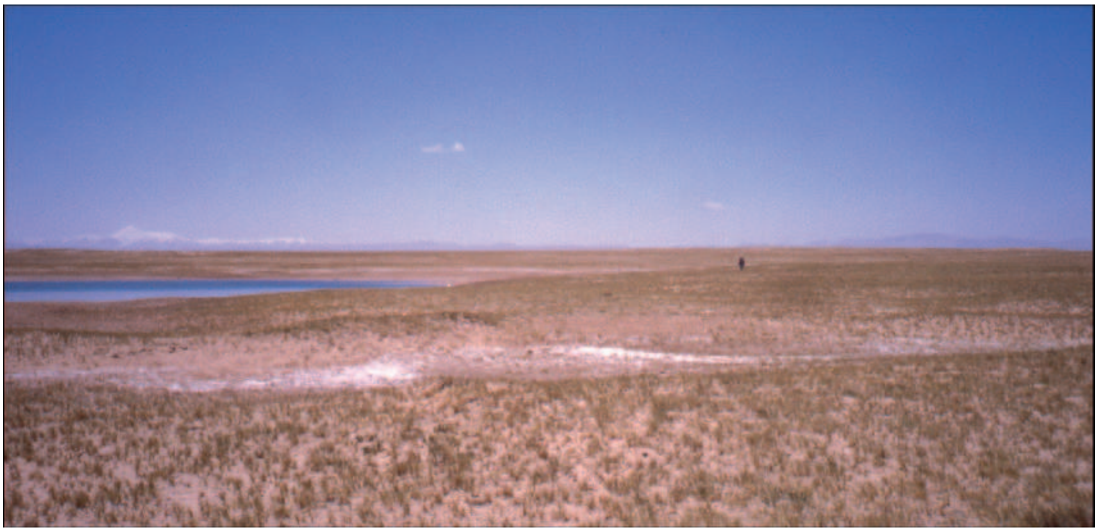

Fig. 8. Typical view of vast treeless plain on the high Tibetan Plateau, south of Kunlun Pass, Qinghai Province.

passed through the region in the late nineteenth and early twentieth centuries. Expeditionary accounts refer repeatedly to wild yaks, yak dung, and its distribution along their routes. For example, William Woodville Rockhill, crossing Tibet in 1891–1892, made numerous notes in his diary about the distribution of yak dung and its importance as fuel (Rockhill, 1894):

[May 30, p. 194] "Fortunately we brought with us several bags full of argols, for there were none to be found anywhere about camp. In this country it is always well to carry a small supply of dry dung, it weighs but little and may often prove invaluable and save one's boxes or pack saddles from being used as fuel."

[June 4, p. 199] "On the way up [a pass] I noticed six yak feeding on the side-hills. The ground was everywhere covered with their dung, so I fancy they are quite numerous in these hills…from the great quantities of yak droppings on this, as on the north side of the range, I fancy that this must be a fine place for a sportsman…"

[June 10, p. 205] "Bunches of yak were on every hill, and that readily accounted for the shortness of the grass in the neighborhood. It is wonderful what huge quantities of grass these animals eat, a herd of a hundred would, I believe, find barely enough on a good, rich meadow three miles square. Fortunately their droppings supplied us with an abundance of much needed fuel, and we were able to keep a big fire burning continually, a thing we have not done for many a day."

[July 4, p. 226] "The ground was soaked, the argols too wet to burn, the only water we could get was muddy and brackish. It was a poor place for a camp, bleak beyond description, the only thing which commended it was the grass. We broke up one of our packing boxes to start a fire and dry some argols for fuel…"

[July 15, p. 243] "The constant heavy rains at this season of the year make traveling in these parts slow, wearisome and difficult, for, to add to the fatigues of the journey, fuel (dung of course) is very scarce, as nearly all is soaked by the rain."

[July 19, p. 247] "Near where we have camped I noticed old fireplaces and other signs that people inhabit this country at some season of the year; it is the highest inhabited spot we have yet met with, its altitude is not less than 16 200 feet above sea level…No dry argols are to be had to-night, and we have had to burn one of our pack saddles…"

[July 20, p. 248] "We passed by quite a number of old camps and pulled down some of the dung walls to get dry fuel. Yak dung is the principal substance used in domestic architecture among the Drupa Tibetans. Besides being used to make low walls around the tents, as is also customary in K'amdo, the people here build little dome-shaped structures about five feet high and six feet in diameter with a small opening in the south side. In these they keep dry sheep's droppings and yak dung for fuel; they also put away in similar storehouses, of which there are a number around each tent, such as their belongings as they don't care to keep inside their dwelling."

Similar tales are recorded in Bower (1893, pp. 388, 394, 398), Bonvalot (1892, pp. 180, 189, 200–201, 206, 208, 231–2, 309–310), Hedin (1905, pp. 100, 142, 405, 424, 429, 444, 459, 465, 474–478, 500–504), and others who traversed Tibet during this period. Wild yak and other native large animals (the kiang, chiru, gazelle, wild sheep, and others) were widespread and often exceptionally abundant, particularly in those large areas of the central Plateau (e.g., the Changtang) where people were scarce (Schaller, 1998). These animals roamed selectively depending on their seasonal habitat preferences, and many parts of the Plateau were not preferred habitat. In some places, large yak herds covered hillsides and pastures with dung, making an argol-collector's as well as hunter's paradise. But long stretches of travelers' trails lacked yaks or yak dung, and the incautious explorer risked burning his pack saddle, boxes, tent poles, whatever, to stay warm. In the rainy season, obtaining quantities of dung dry enough to burn may have entailed prolonged processing. Prudent long-term survivors on the Tibetan Plateau made sure they had sufficient fuel available to them wherever they happened to be. Foragers coping with spatial discontinuities in dung fuel may have ensured an adequate supply of this essential resource by "mapping on" to likely dung-rich areas, e.g., by following yak herds and their trails or by focusing on yak's preferred habitats; or by using various logistical strategies to bring fuel to their camps, e.g., collecting and drying yak dung to carry with them, transporting dung fuel to base camps for processing and use, or bringing captive yaks with them – the last of these a potential step that may have helped to initiate the yak's domestication.

6. Yak Domestication and Yak Dung

6.1 How and Why Were Yak Domesticated?

As noted above, little is known concretely about the process of yak domestication, even the specifics of place or time (Palmieri, 1976; Clutton-Brock, 1981; Bonnemaire, 1984; Olsen, 1990; Flad *et al.*, this volume). Why the wild yak gave rise to a domestic stock is itself something of a mystery, as with other cattle (Clutton-Brock, 1981, p. 66). Most species of mammals are unsuited to domestic life, and only a very few have become successfully domesticated (Baskin, 1974; Diamond, 1997). These few domesticates tend to possess physiological and behavioral characteristics that fit well in a human–animal mutualistic relationship, including relatively high productivity (somatic or reproductive), generalized and usually herbivorous feeding behavior, gregariousness, nonterritorial mating systems, hierarchical group structure, and polygamy (Walther *et al.*, 1983; Garrard, 1984; Rowley-Conwy, 1986). At first sight, the wild yak would seem to make a poor candidate for domestication: it is very large and reproduces slowly, is generally unruly and flighty around people, and can be very dangerous (cf. Diamond, 1997, pp. 168–174). It inhabits one of the most isolated and least hospitable places on earth for human occupation, affording little opportunity for close and sustained interactions with humans or for the development of human social, demographic, and ecological factors that appear to promote domestication (e.g., moderate to high population density, settled communities, territoriality, and overhunting around settled communities; Hayden, 1995). So why, then, were yaks domesticated?

Despite their shortcomings, several characteristics of the wild yak must have facilitated domestication. One is social structure: yaks form close-knit herds of cows, calves and young males with a well-defined dominance hierarchy but are not strongly territorial (Schaller, 1998). This trait gives individual animals a sense of herd membership or social "place" that can be exploited by people to control captured animals. Like other cattle, cows and calves also exhibit strong interanimal imprinting (Schaller, 1998; Wiener *et al.*, 2003), a behavior trait that can also be manipulated by herders to advantage. Captured animals with this set of social rules may become imprinted onto a person as the dominant herd leader or may be readily fitted into the established hierarchy of a domestic herd (Diamond, 1997, pp. 172–174).

Another behavioral characteristic is that yaks instinctively tend to bunch up in stressful situations to protect themselves against predators or while traveling together along narrow trails; such "bunching" behavior may make captive animals better suited to confinement in corrals or pens. If social structure and behavior were central to the yak's domestication, then the wild yak was most likely to have been domesticated when people who already managed domestic herds entered the Tibetan Plateau. The social structure established between herders and their herds would have most easily been able to incorporate captured wild yaks.

A third characteristic promoting domestication may be the wild yak's isolation. Genetic segregation of a breeding population must have been essential to the yak's domestication, and selective forces leading to domestication could not be sustained without segregation from wild herds. We should therefore expect that yak domestication required separation from the main distribution of wild yaks, where genetic isolation of small breeding populations could be effectively maintained. This probably occurred on the fringes of the Tibetan Plateau, below the optimal altitude range of wild yaks, but not so low that domesticated yaks would lose their adaptation to high altitudes (whether wild yaks brought to lower elevations become more tractable and docile is not known). Alternatively, captive yaks may have been effectively segregated from breeding with free wild yak by the wild yak's apparent wariness when people are around.

Most importantly, yak domestication should have become important only when people made sustained settlement of the Tibetan high country, where yaks are eminently adapted for survival and domestic cattle are emphatically not. Yaks have a reputation for not thriving below 3000 m (though many populations of domestic yaks do exist below this altitude; see Weiner *et al.*, 2003, pp. 337–346). In competition with domestic cattle, yaks would not be selected for at low elevations. Yaks would only be preferred at higher altitudes where they outperform cattle (e.g., above 2500–3000 m elevation) and would only be preferred if people had opted for sustained occupation at those high altitudes themselves. It is likely that this preference occurred in the context of the development of farming and herding communities on the margins of the Tibetan Plateau during the Mid-Holocene, such as the Zongri complex in the upper Huanghe (Yellow River) drainage (Chen *et al.*, 1998; QSWG/HZMB, 1998; Chen, 2002; cf. Aldenderfer and Zhang, 2004; Rhode *et al.*, nd; Aldenderfer, this volume).

Yak domestication must have occurred under conditions in which the benefits of conserving yak for future use outweighed the immediate gains of hunting them (Alvard and Kuznar, 2001). In this shift from hunting to animal husbandry, "we went from exploiting the somatic potential of other organisms to co-opting and increasing their reproductive potential" (Alvard and Kuznar, 2001, p. 295). The costs associated with animal husbandry increases for large animals and those with low reproductive rates: future gains simply do not outweigh immediate payoffs, given opportunity and discount costs. With their great size and slow intrinsic rate of population increase, wild yak find themselves firmly in the "hunt" category (a feature they share with most major domestic animals). Mitigating factors must have made yak husbandry more beneficial than yak hunting, including the need for products such as dung or transport energy (so-called secondary products; cf. Sherratt, 1981), reduction of risk (Mace, 1993), or longer-duration planning for the future (Alvard and Kuznar, 2001, p. 306). Of these, the utility of secondary products such as dung and transport may have had the most immediate benefit to occupants of the Tibetan Plateau. If a kept animal "earns its keep" by delivering other important products besides its meat and skin, then the opportunity and discount costs of keeping it alive are reduced, and husbandry becomes as profitable as hunting. Behaviors that reduced risk may also have been strongly favored in the unpredictable Plateau environment, particularly during the Mid- to Late-Holocene transition ca. 4500 BP when the Tibetan environment became significantly colder and harsher. One such risk-reducing behavior may have been to ensure that a steady supply of fuel was available by keeping one's own fuel-producing herd near to hand.

6.2 *Was Yak Dung a Factor in Domestication?*

Could yak dung have played a role in the development of a mutualistic bond between yaks and people, eventually leading to the domestic yak and yak-pastoralist? Before yaks were domesticated, wild yaks could supply people with dung, meat, hides, and hair, and occasionally live calves that might be captured for pets (Serpell, 1989) or to lure other wild yaks to congregate near hunters (as was once suggested for domestic reindeer; Hatt, 1919). Contributions such as milk or transport could not be expected from wild yak. Of the two main critical commodities, meat and fuel, yak dung was the most abundant and most likely to be obtainable on a regular basis. From a purely energetic point of view, yak dung could have been as important as any other product obtainable from the wild yak.

To compensate for the patchy distribution of dung on the Plateau landscape, people could pursue one or more solutions: (a) bring yak dung or other fuels with them on their travels through areas that lack yak; (b) follow the herds using yak dung as they trail along, and avoid areas where yak do not go; and (c) procure and maintain wild yaks to produce dung wherever they camp.

If people used only option (a) and carried dung or other fuels with them, no domestication relationship should be expected since people would not develop a reliance on either yaks or yak dung, and yaks would develop no mutualistic tie to people. As Rockhill (1894, p. 194) advised, prudent foragers would carry some dried yak dung to tide them through places where other fuel sources were not expected to occur. Light as dried yak dung may be, it can be bulky, and carrying around significant quantities without effective means of transport (i.e., pack animals) appears unlikely. If it takes 2–3 l of dung to boil 1 l of water over an open fire (see above), the volume of dung that a person would need to carry for even short trips of a few days in fuel-less terrain could quickly become unwieldy, though not especially heavy. Similar problems attend transport of other energy-rich but voluminous resources: small amounts are ideal, but large quantities are prohibitive for pedestrian foragers (e.g., Madsen and Kirkman, 1988; cf. Jones and Madsen, 1989; Metcalfe and Barlow, 1992).

If people followed the herds (option b), they might become dependent on yaks and yak dung, but no reciprocal reliance would develop on the yak's part, any more than in other predator–prey relationships (cf. Wilkinson, 1972). Wild yak herds would experience no selective pressures to become attached to humans; indeed, human predation would most likely exert selective pressures on wild yaks to flee fast and far, as they do nowadays in response to hunting pressures (cf. Hedin, 1905; Schaller, 1998).

If people used option (c), however, captured wild yaks could have been kept as camp animals (Olsen, 1990, p. 89) to provide dung, carry loads, and eventually to provide other products such as hair and milk. In short, people who settled in the high Plateau may have relied on yak dung as fuel and in the process became yak followers, which afforded opportunities to capture and isolate wild yak individuals that would serve as a reliable source of dung and, later on, other useful products.

These scenarios are of course not mutually exclusive. They highlight the evident conclusion that yak domestication must have required capture and reproductive isolation of wild stock in some manner. They implicate yak dung as one main product that could be obtained in early phases of an emerging human–yak mutualistic relationship.

Counterarguments against the notion that yak dung was an important element in the yak's domestication can of course be mounted. Most obviously, merely following the herd will not by itself result in domestication, even if individual animals were occasionally captured and kept. There is no necessary reason that collecting yak dung by itself significantly alters the selective landscape sufficient to force significant changes in the behavior, morphology, or genetics of the yak.

Second, other fuel might be available. In some areas, wood from small shrubs and bones or horn splinters were usable as fuel (Rijnhart, 1901; Hedin, 1905, p. 444, 468), but the historical records and our observations of high Plateau vegetation suggest that these fuel sources are less abundant than wild yak dung. Other herbivores produce large serviceable quantities of dung, notably the wild ass or kiang, but kiang dung is less suitable for fuel than yak dung, as Abbé Huc noted long ago. Wood was available on the Plateau's margins and may have been more common during the early period of human occupation, but as noted before, most of the Plateau would have been woodless even during the Holocene climatic optimum. Sheep dung may have been a useful and abundant fuel, if the traveler was a shepherd with flock. Sheep pellets are commonly used as fuel in parts of the Tibetan Plateau, burning hotter than yak dung but requiring a bellows to stay ignited in the thin oxygen of the high plateau (Goldstein and Beall, 1990, p. 35). It is harder to collect than yak dung, unless the sheep are penned or confined to close quarters. Sheep droppings would not be a ready option for hunters or pre-pastoralists, of course.

Third, it may be argued (from an intentionalist perspective) that yak dung was not the reason for occupying the high Plateau and therefore not for domesticating yaks while there. People would not have made the arduous journey to the high Plateau solely for the purpose of collecting yak dung (though some people do so nowadays): hunters would have traveled there in search of wild game, pastoralists in search of luxuriant meadows for their herds, bandits in search of hunters or pastoralists to attack. Despite these intentions, however, all of these people would have required fuel to stay on the high Plateau for any appreciable length of time, and yak dung was one of the best fuels available in the high country.

Fourth, there is no evidence that processes resulting in the domestic yak involved selection for enhanced dung production. Quite the opposite: dung production is tied to body size and diet, and the process of yak domestication selected for a reduction in body size along with increased docility and tractability, which probably resulted in lower individual dung production rates. Overall usable dung production could have been enhanced with a domestic herd, thereby raising the unit of selection from the individual to the group; but it is difficult to imagine a successful group-selectionist domestication process involving a herd of unruly wild yaks, selected as a herd for the purpose of enhanced dung production. More likely, increased dung production would have been the outcome of selection favoring yaks that could live in domestic settings (docility, adherence to a dominance hierarchy led by people or their herding dogs, etc.), which would have made greater quantities of dung more readily available close to peoples' camps.

Ultimately, the process of domestication entails a shift in emphasis from an interest in the dead animal (its meat or hide) to an interest in the maintenance of the living animal and, more important, its progeny (Meadow, 1989; Alvard and Kuznar, 2001). Keeping a stock of animals for whatever reason (and a ready supply of useful dung can be one very good reason) becomes an end in itself and better to keep a reproducing stock than to constantly replenish it from the wild. At that point, the importance of dung fuel as a driver in the relationship between yaks and people would become only one of several products that a kept herd could provide.

Given these considerations, yak dung collection may have been an important element linking people to yaks at an early stage in the process of yak domestication, but it is unlikely to have been fully responsible for that process. Yak dung can be seen as one important resource, one that people are likely to have depended on, preceding the use of other important resources such as milk and transportation. Considering yak dung in this light highlights the continuum of behaviors linking people to other animal species, ranging from simple to not-so-simple predator–prey dynamics, to capture-keeping relationships, to full-scale domestication (Wilkinson, 1972).

6.3 Yak Domestication and the History of Human Settlement of the Tibetan Plateau

Based on these considerations, a speculative model about the timing and context of yak exploitation and eventual domestication can be developed. As outlined in Brantingham *et al.* (this volume; also Madsen *et al.*, 2006), Upper Paleolithic foragers began to occupy the mid-elevation fringes (~3000–3500 m elevation) of the Tibetan Plateau by ca. 15,000 Cal yr BP. These small mobile hunting parties, whose forays were probably limited seasonally, may have encountered herds of wild yaks (depending on the season of occupation of the mid-elevation step), but no evidence yet exists that they hunted yaks, let alone domesticated them. It is unlikely that yak domestication occurred in this context.

During the Early Holocene, Upper Paleolithic and Epipaleolithic hunters made sustained forays into the high Plateau (>4000 m), possibly as a result of competitive displacement by farming groups at lower elevations, possibly in response to expanded habitat during the Holocene climatic optimum (Madsen *et al.*, 2006; Rhode *et al.*, 2007; Brantingham *et al.*, this volume). These groups undoubtedly encountered wild yaks and likely used yak dung for fuel in the high country. Whether they hunted yaks or scavenged winter-killed yaks for food or became yak-herd followers is not known. Available site assemblages suggest a mobile foraging strategy with some evidence of residential bases at marginal elevations (e.g., Jiangxigou 2, near Qinghai Lake, and Layihai on the upper Huanghe; see Brantingham *et al.*, this volume; Gai and Wang, 1983; Rhode *et al.*, 2007). This initial sustained colonization of the high country could mark the inception of yak domestication, but evidence is currently lacking. No evidence of yak exploitation is known from these sites, and the keeping, transporting, and maintaining a genetically isolated breeding population of captured wild yaks appear unlikely.

During the Middle Holocene, small communities of mixed hunting and farming economic orientation began to appear on the margins of the high Plateau, as at Zongri (Chen *et al.*, 1998; QSWG/HZMB, 1998; Chen, 2002) and Karuo (CPAM, 1985; Aldenderfer and Zhang, 2004). These Neolithic villages, related to central Chinese Yangshao agricultural complexes but also derived from local Tibetan antecedents (Chen, 2002; Aldenderfer, this volume) contain substantial architecture, graves with grave goods, sophisticated ceramics and bone and polished stone tools, as well as evidence of domestic cattle and other domesticated plants and animals along with abundant remains of wild game presumably from local and higher-elevation contexts (Flad *et al.*, this volume). Yak remains are not known from these sites, but it is possible that at this time people captured wild yaks and transported them to settlements on the Plateau margin, gave them limited feed to reduce their size and make them dependent on people (Lu, 2000), and possibly plied with salt to tame them (cf. Palmieri, 1976), resulting in isolated populations in the first stages of domestication. If captive breeding occurred, then domestication would have been well under way. It should be reiterated, however, that evidence for yak remains at these sites is currently absent, so this scenario is entirely speculative.

Finally, toward the end of the Middle Holocene, pastoralists began to bring domestic sheep herds into the high Plateau pastures on a regular seasonal basis. The timing of the inception of sheep pastoralism in the high Plateau is not well established, but domestic sheep are archeologically known from northwest China dating to at least 4000–5000 BP (Flad *et al.*, this volume). The onset of sheep-herding in the high Tibetan Plateau was likely to have been a major impetus for yak domestication. Sheep-herders must have encountered wild yaks on the high Plateau and may have captured and tamed individual wild yaks, eventually segregating and taming a breeding population within their own herds (in keeping with the traditional historical accounts of the Qiang people). This process was likely facilitated by trading captured and tamed yaks to cattle-raising farmers at lower elevations, who may have crossbred them with yellow cattle to create hybrid *dzo*, and possibly raised purebred yaks as breeding stock.

Once yak were domesticated, the high Plateau opened up to human occupation in ways not possible before. Sheep pastoralism in the high country is viable seasonally but not year-round (Goldstein and Beall, 1990; Stevens, 1993). Yaks can survive in the high country year-round, so a more intensive pastoralist occupation of the high country was possible. Yaks are able to survive on the scant alpine vegetation better than sheep. Most important, yaks can carry much more equipment than sheep, including the heavy tents used for shelter. With the use of yaks as animals of traction, the long distances of the Plateau became manageable for people, and with their yak's help, they could bring what they needed to survive in the high country on a more permanent basis, including a ready supply of dung fuel. But whether yak domestication began during a pre-pastoral hunting mode of occupation of the Tibetan Plateau or during a subsequent pastoralist occupation of the Plateau must yet be determined through archeological investigation focusing on the nature and timing of early occupation of the Tibetan Plateau itself and of Neolithic farming and herding communities on its fringes (Huang, 1994; Chen *et al.*, 1998; Brantingham *et al.*, 2001; Chen, 2002; Brantingham *et al.*, 2003; Aldenderfer and Zhang, 2004; Brantingham *et al.*, this volume).

To recapitulate, our current evidence for the timing of yak domestication, limited though it is by the paucity of the Tibetan archeological record, suggests that it most likely occurred in the context of the occupation of the margins of the high Plateau by mixed farming/hunting groups who maintained herds of domestic cattle after ca. 6000 years ago, and especially in the context of the establishment of sheep pastoralism ca. 4000–5000 years ago. Much more archeological work is needed to clarify the processes, geographic distribution, and timing of yak domestication.

7. Summary

Yaks are a fundamental part of traditional Tibetan society and must have been crucial to the development of that culture in prehistory. One of the important products of yak is dung, used for a variety of purposes but especially as a fuel for cooking and heating. This paper described the energetics of yak dung and its contribution in relation to other products of the yak, demonstrating that dung is one of the largest energetic contributions the yak delivers. The importance of yak dung to Tibetan yak pastoralist society has been noted by nearly every visitor to the country, but yak dung was probably equally important to the hunters and foragers that preceded the yak pastoralists in settling the high Plateau. Indeed, yak dung may have been an important element in the early development of yak domestication. This domestication process may have occurred in the context of initial sheep pastoralism some time prior to ca. 4000 BP, but much is left to be learned about the history of pastoralism on the Tibetan Plateau and the yak's role in it.

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Part V

SUMMARY AND INTEGRATION

13

Changing views of Late Quaternary human adaptation in arid China

David B. Madsen, Chen Fa-Hu and Gao Xing

Abstract

This volume presents a number of models exploring the relationship between climate change and cultural evolution in arid China. Together, they suggest rapid climate change events leading to millennial-scale environmental shifts likely triggered many of the significant cultural changes involved in the Paleolithic to Neolithic transition. The impacts of these events differed, however, depending on sociological and technological conditions. These shorter-term climate events were imposed on the more long-term transition to the Holocene that promoted the advent of millet agriculture and the development of pastoral societies.

1. Introduction

In the introduction to this volume, we pointed out that our understanding of the human response to the Pleistocene/Holocene transition in arid China has increased markedly in the last two decades. Much of this has been due to a concomitant increase in the definition of sub-Milankovitch scale climate change cycles associated with the transition and to an increase in chronological controls suggesting that a correspondence between many environmental and cultural changes may exist. Prior to the last decades of the twentieth century, archeology in arid China was principally limited to description and to classification schemes distinguishing the core-and-blade industries of the Paleolithic from the microlithic technologies, ceramics and village architecture that marked the advent of the Neolithic. More recently, environmentally structured research has moved archeology in China beyond mere classification and description toward the identification of explanatory mechanisms that may underlie the changes seen in the archeological record. As a result, it now seems rather straightforward that abrupt and dramatic climate changes may be the root cause of many of the social changes in that record. What is relatively unknown and relatively unexplored are how and why these social responses occurred in the ways that they did. This volume represents an attempt to move past descriptive classification and simple environmental determinism by presenting a series of testable models exploring the relationships between climatic and cultural change in arid China. By presenting these models together, we hope to make it possible to guide research in the near future toward the examination of their explanatory utility. Here, we attempt to summarize these diverse models and suggest ways in which they may be tested.

2. Rapid Climate Change and Cultural Adaptation

As the review chapters in Part II make clear, the environmental history of arid China spanning MIS 3–1 is relatively well known (but see Herzschuh and Liu, this volume), at least in comparison to the archeological record. Much of this is due to the availability of long-term, high-resolution records from a variety of environmental climate proxies such as loess, lake, pollen, ice core, and speleothem sequences. What these detailed records suggest is that the shift in the location of the summer monsoon margin, in response to both long- and short-term climate change events, was likely one of the major driving forces in structuring cultural change in arid China. At its maximum, the summer monsoon may have reached as far as the southern margin of the Gobi desert and the eastern edge of the Tarim Basin, while at its minimum, its effect may not have reached much of the western and northern Loess Plateau.

The human impacts resulting from this shift appear to have differed somewhat depending on its length and intensity. From what little evidence is available (Barton *et al.*, Bettinger *et al.*, Brantingham *et al.*, this volume), it is apparent that Milankovitch-scale, long-term shifts of the monsoon margin to the southeast, in conjunction with the colder temperatures with which these shifts were associated, may have resulted in long-term changes in the density and distribution of foraging populations, together with a shift in mobility and a general broadening of the diet to include such low-ranked resources as millet seeds. These long-term climate changes may thus underlie the basic shift from the Paleolithic to the Neolithic during the Pleistocene/Holocene transition. Bettinger *et al.* (this volume, see also Richerson *et al.*, 2001), for example, suggest these Milankovitch-scale trends were ultimately responsible for the development of agriculture. However, while the overall trend may have been a gradual long-term change, this trend was the sum of episodic events, and these shorter-term, but intense, centennial- to millennial-scale shifts in the monsoon appear to have acted as "triggers," driving dramatic sociological and technological changes.

It is possible that the differential effects of these long- and short-term environmental impacts can be explained by a model of cultural evolution characterized by "adaptive peaks," first posited by Boyd and Richerson (1985).

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In this model, cultural change proceeds through a trajectory of peaks and valleys, with a particular technology and adaptive strategy changing slowly through numerous small refinements in response both to internal improvements and to gradually changing social and environmental conditions. As these improvements accumulate, so too does the population using them. Over time, these refinements approach the maximum fitness of that particular technology and adaptive strategy, but shifts to major new approaches do not immediately occur because of the costs involved in making those shifts. Minor changes in the relationship between the adaptive strategy and the environment may cause a temporary decrease in efficiency, but unless the change is sufficiently major, the direction of adaptive modifications is simply back toward the initial peak (Fig. 1A). Eventually, however, the population reaches the strategy's viable limits and major shifts in the social or physical environment can trigger a collapse into a valley. At that point a new and more viable technological/adaptive system can take root and the cycle repeats itself. These tipping points can be the result of any number of factors ranging from internal social dynamics to war to disease epidemics, but a major trigger appears to be a dramatic shift in the nature of the resource base on which that society is dependent. As a result, abrupt and dramatic climate change events can induce rapid cultural changes when they significantly alter the composition of the resource base and/or its productivity, and, in turn, the relationship between resource abundance and population (Fig. 1B).

In short, and as virtually all of the archeological papers in this volume point out, most of the major abrupt climate change cycles of the last 30,000 years in arid China appear to be associated with shifts to new technologies or adaptive strategies. Among early foraging societies, and during the transition to the Neolithic, most of these appear to be related to Heinrich Events (assuming that the Younger Dryas can be considered a Heinrich Event). Brantingham *et al.* and Barton *et al.* are the most specific about the identification of these events and use the Hulu Cave speleothem record to provide a detailed chronology for these events. They identify Heinrich pulses H3 (~31 Cal ka), H2 (~24 Cal ka), H1 (~16 Cal ka), the Younger Dryas (~13 Cal ka), and the North Atlantic flood-induced cooling at ~8.2 Cal ka, as key rapid climate change events that had dramatic impacts on technological and/or social change in arid China. While minor oscillations occurred between these events, they were not apparently of sufficient magnitude to shift the local adaptive strategies beyond their initial trajectory.

We should reiterate that these events acted only as "triggers," and that their impacts differed depending on environmental conditions, adaptive strategies, population levels, and technological complexity that were interacting in particular localities. For example, the ~8.2 Cal ka event may have triggered the rapid adoption and spread of village agriculture on the Loess Plateau (Bettinger *et al.*, this volume), while similar, but earlier, climate change events did not, because of the prolonged period of seed utilization that preceded it. In the arid northern desert and western highlands regions of China, the intense cold/dry climates associated with Heinrich Events appear to have reduced population levels or forced regional abandonment altogether (Ji *et al.*, 2005; Brantingham *et al.*, this volume). In the more southern deserts and grasslands, on the other hand, these events appear to have fostered reduced mobility and an increase in occupational intensity in areas that may have served as refugia (Barton *et al.*, this volume). Although data are sparse, foragers appear to have reoccupied the upper margins of the Tibetan Plateau during the warmer intervals immediately following Heinrich Events (Aldenderfer, this volume; Brantingham *et al.*, this volume), and there is an apparent decrease in occupational intensity in the arid deserts and Loess Plateau (Barton *et al.*, this volume). These changes suggest adaptive responses were related more to shifts in areas of occupation and degrees of residential mobility than to marked reductions or increases in overall population size.

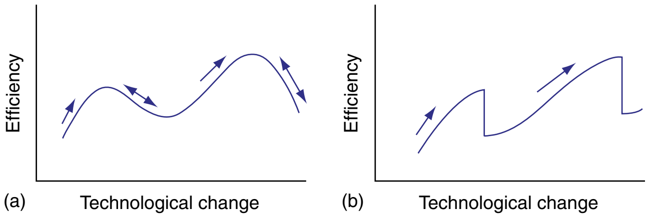

Fig. 1. Schematic representation of how abrupt climate change events MAY alter the expected trajectory of technological evolution: (A) Successively more efficient adaptive peaks (where efficiency equals the energetic return per unit of effort). Major technological shifts occur when overall efficiency is reduced to the point where a new, but unrefined, technology is equal to or more efficient than an older, more completely developed technology. (B) Similar series of adaptive peaks with decreasing efficiency accelerated by rapid climate change events.

3. Modeling Adaptive Shifts in Arid China

The papers in the volume contain a variety of both explicit and implicit models explaining technological and/or adaptive shifts in the semi-arid to arid regions of northern and western China over the last 30,000 years. Most of these models are based on rather limited data and are likely to be revised or abandoned as our understanding of cultural change in the region increases. Despite this limitation, the models are useful as guides as to how we might go about looking for explanations of the sometimes dramatic cultural events of the Pleistocene/Holocene transition, where to look for them, and what to look for.

Madsen and Elston and Barton *et al.* each provide models of how the transition between the Early Upper Paleolithic (EUP) core-and-blade technologies and adaptive strategies and the microlithic technologies and adaptive strategies of the Late Upper Paleolithic (LUP) may have played out. While the models differ, they are more complementary than they are contradictory. The transition, reduced to its simplest levels, involved a shift from high-mobility movement across a relatively uniform environment, together with the pursuit of relatively few high-return resources, to a pattern of restricted mobility in more isolated regions of high resources productivity with a focus on a broader array of resource. Sites like Shuidonggou (Madsen *et al*., 2001; Gao *et al*., 2002) are characteristic of the earlier strategy, while sites such as Xiachuan (Chen and Wang, 1989) and Pigeon Mountain (Elston *et al*., 1997) are characteristic of the later adaptation.

Madsen and Elston, using optimal foraging models, contend this shift may be explained by a simple expansion of diet breadth, with foragers adding a greater variety of low-ranked plants and animals to their diets, thus enabling them to stay longer at any one location. A major consequence of reduced mobility is that the access to toolstone sources is also reduced, necessitating a greater emphasis on maximizing the number of cutting edges produced from a given quantity of stone. As a result, along with a shift in mobility, there was shift from the wasteful "smash-and-bash" bipolar production of bladelets for inset tools to a more careful production of more numerous microblades from a single prepared core. Barton *et al*. do not disagree with this basic model; rather, they expand it to suggest that the transition was facilitated by a change in the social structure of foraging populations in arid China. Specifically, they suggest that as a result of demographic packing, there was a dramatic increase in "group-beneficial behavior" between the EUP and the LUP that was marked by the spread of social boundaries, signs of group identity, and the sharing of resources within each group. They also contend that such group-beneficial behavior may help explain the rapid spread of microlithic technology.

So, how can the utility of these models be tested? Madsen and Elston suggest several tests for their model, but essentially these boil down to identifying a change in the distribution of archeological sites through time. This is relatively simple, albeit costly and time-consuming, as it entails the accumulation of survey date from the rather large arid landscape of northwestern China. Limited data accumulated to date do suggest the model may have some validity, but these data are too few and too spatially scattered to move the model much beyond interesting speculation. It does, however, provide a guide as to the kinds of future research that might be most productive. The model proposed by Barton *et al*. is even less susceptible to test, not because the behavior predicted by the model does not produce identifiable results, but because they are more difficult to find. They suggest that one of the consequences of group-beneficial behavior is the emergence of "ethnic markers" that serve to identify group members and group boundaries. Unfortunately, such stylistic variations are most likely to be found on articles of clothing, adornments, and the soft parts of weaponry (e.g., Sinopoli, 1991), rather than on the stone tools that constitute virtually the entire corpus of material remains at most Paleolithic sites. One exception may be the presence of unique kinds of exotic toolstone in a particular area or set of sites from sources beyond where direct acquisition is likely to have occurred. This would suggest internal group exchange, while differences between groups would be suggested by different kinds of exotic toolstone among different sets of sites. Thus, if we were to take from this model a guide to future research it would be the need to identify toolstone quarries and the particular chemical identity of the stone from those quarries for use in mapping out group territories.

Bettinger *et al*. and Madsen and Elston both take on the knotty questions of how, when and why millet agriculture developed along the margins of the summer monsoon. Here again, these models are complementary rather than contradictory, with Madsen and Elston focusing more on the timing and location of initial seed manipulation and Bettinger *et al*. focusing more on the rapid spread of millet-based village agriculture following the initial experiments with seed production. Madsen and Elston suggest foragers developed an initial dependence on seed use during the period before and during the Younger Dryas as part of an overall increase in diet breadth. Collecting and processing techniques were improved during a period of climate amelioration after ~10 ^{14}C ka when wild millet seed patches on the northern desert margins of its range were enhanced and most productive. As these patches were reduced and eliminated, foragers, now dependent on these seed resources, began to plant, cultivate and select the most productive variants, setting the basis for millet agriculture.

Bettinger *et al*. suggest ways in which these "low-level food producers", as they term them, developed full-blown millet agriculture. They contend this development most likely involved the establishment of group control of particular resource patches. The group selection processes resulting from this group, as opposed to individual, control helped bridge the gap between periods when individuals might be expected to shift back to full-time foraging. The Bettinger *et al*. model further suggests that low-level millet food producers employing group ownership strategies moved south into the Loess Plateau after about 8 ^{14}C ka where they found their initial crop production along the oft-flooded river margins was improved. The success of full-time farming was, they contend, at least partially due to the absence of many foragers in the northwestern Loess Plateau; an absence that allowed group ownership to succeed and village agriculture to quickly develop and spread, without the competition for resources that would retard its development.

Archeological tests of both models are largely dependent on chronologically controlled survey data. That is, forager sites dating to 10–8 ^{14}C ka should be common in areas along the southern margins of the Tengger and Mu Us deserts in locations suitable for the growth of wild millet. Many of these sites should contain evidence of relatively long-term, perhaps seasonal, stays. During the same period in the northwest Loess Plateau, on the other hand, forager populations should be reduced during this period. As Bettinger *et al*.

note, there is already some support for this model in the Loess Plateau portions of Gansu Province, although much more survey work still needs to be done. Further to the north, survey data are so limited as to preclude anything beyond speculation.

What may be less susceptible to archeological test is the notion that group "ownership" of particular resource patches was the driving force behind the development of full-blown agriculture. There is something of a chicken-and-egg problem with this idea, as it is difficult to determine which came first: continued use of a particular patch by a family or multi-family group leading to the defense of something important to their survival and which they consider to be theirs or that the concept of landscape control developed first followed by a search for and occupation of areas best suited for ownership? Put another way, what constitutes an archeological test of "ownership?" Certainly, evidence for permanent structures and the continuous occupation of an area would provide some support, but that would come only after the development of settled village agriculture and, thus, tells us little about the basis for that development. In short, some aspects of the model are more amenable to archeological test than others. That does not mean the model is wrong, only difficult to test. Beyond that, we find it somewhat ironic that after a shift away from the dominance of Marxist theory in Chinese archeology, western archeologists have now reintroduced the notion that corporate control of land is critical in the development of settled village agriculture.

Aldenderfer and Brantingham *et al.* explore models for the initial peopling of the cold, arid uplands of the Tibetan Plateau and the appearance of Neolithic pastoralism in this extreme environment. While both models suggest foragers may have occupied at least the margins of the upper plateau by 30–20 ^{14}C ka, they appear to differ in significant respects. Aldenderfer (see also Aldenderfer and Zhang, 2004) has EUP foragers in the interior plateau before the Last Glacial Maximum (LGM) and contends that foragers occupied the interior plateau on a full-time, year-round basis by at least the LUP. Brantingham *et al.* (contra Brantingham *et al*., 2001b), on the other hand, suggest surface sites in the interior, previously thought to date to the EUP, probably date to after the LGM, or, more likely, to the Early-to-Middle Holocene. The differences in the models may be more apparent than real, however, since the single direct age cited by Aldenderfer in support of an early year-round occupation of the interior plateau is only about 9.4 ^{14}C ka and has a standard deviation of 1400 years. Thus, the site likely represents a post-Younger Dryas occupation and may actually be close in age to those cited by Brantingham *et al.*

The Brantingham *et al.* model further provides several alternative explanations for the Holocene "colonization" of the plateau by groups related in one way or another to Neolithic communities to the east. The alternatives include "adaptive radiation," "directional selection," and "competitive exclusion," but all involve change in the nature of populations in low-elevation source areas. While they suggest these processes led to movement onto the plateau by "dedicated foragers" during the Early-to-Mid Holocene, they raise the possibility that permanent occupation was impossible without the support of agriculture and related pastoralism. Aldenderfer also explores possible "demic" movement of Neolithic groups dependent on domesticated animals and plants onto the plateau, but additionally discusses possible routes for that movement. The two most likely emigration routes seem to be through mid-elevation staging areas in Sichuan Province to the southeast and Qinghai Province to the northeast, though over the Himalayas from the south is also a remote possibility. He notes that clarifying these routes is important in understanding how modern pastoralists in the region became dependent on yak and barley as their major food resources. It is interesting to speculate that a wild barley, adapted to harsh high-elevation conditions, may have been independently domesticated. If so, it would go a long way toward explaining how full-time foragers may have occupied the region and how the yak- and barley-based pastoralism of the present may have developed among indigenous foragers rather than from expanding populations from the lowland.

Archeological tests of these models may be difficult, as they are both wide-ranging and multifaceted. We would reiterate Aldenderfer's point that explanations of the Tibetan Neolithic are likely to be complex and necessarily take on a "mosaic character." Any single archeological test or set of tests is likely to be inadequate in addressing such a mosaic. However, certain aspects of these models are amenable to archeological and ethnoarcheological testing. For example, determining whether the interior plateau was first occupied by full-time Paleolithic foragers or by Neolithic pastoralists may be resolved by locating and excavating stratified sites containing these components. Such sites may be difficult to find, but it would seem that the burden of proof would be on the backs of those supporting an early full-time foraging adaptation. Modern occupants are so dependent on domesticated animals and plants for survival it is difficult to understand how foragers could survive year-round at those altitudes. If, however, one could find deposits dating to the pre-Holocene that contain the wild equivalents of these resources, it would go a long way toward supporting that argument. In addition, it would be useful to conduct ethnoarcheological return-rate tests (e.g., Simms, 1987) of available plant resources to see if any could potentially help support a foraging group on a year-round basis. As Aldenderfer notes, there are few, if any, pastoralists completely dependent on meat, and entirely carnivorous foragers are also rare. As a result, it is likely foragers occupying the plateau on a year-round basis were dependent on vegetative resources to some extent. Certainly, locating evidence of a possible wild barley is a step in that direction, but construction of a testable diet model including plants would help in supporting the notion of early foraging populations on the plateau.

Finally, both Flad *et al.* and Rhode *et al.* take on issues of animal domestication in arid China. Flad *et al.* note that, with the possible exception of camels and yaks, all domesticated animals in arid China appear to have been introduced from other areas. For the most part, these domesticated animals are apparently derived from the Near East and central Asia, probably along traditional "Silk Road" routes. The principle exception is the pig, which may have been domesticated in multiple locations to the south and east and introduced into arid China from those directions. Given this probable Silk Road route for the introduction of such animals as sheep, cattle, and goats, it is interesting to speculate that such herd animals may have appeared in the Hexi Corridor along the northern and eastern margins of the Tibetan Plateau prior to their adaptation elsewhere in China. If so, both village pastoralism and fully nomadic pastoralism may also have developed along with millet agriculture earlier in this corridor than elsewhere. As yet, there is little evidence for this, primarily because of the difficultly in separating domestic from wild variants of sheep and goats in the absence of large faunal collections. If this turns out to be true, however, it may be that the earliest nomadic pastoralism in the Tibetan Plateau margins was based on sheep pastoralism long before yak pastoralism became fully developed (e.g., Rhode *et al.*, 2007). While the model is yet speculative, it does match what is known about the genetic history of modern Tibetans (Su *et al.*, 2000).

Rhode *et al.* suggest just such a process may have been involved in the domestication of the yak. That is, sheep pastoralists first encountered yaks along the margins of the Tibetan Plateau at the lower margins of their natural distribution and began to incorporate captured wild yaks into their herds. They speculate that the need for dung may have been a partial driving force, as slowly moving sheep camps would quickly deplete any one location of the wild yak dung used as a principal fuel source. Rhode *et al.* also conjecture that the presence of cattle among farmers at lower elevations may have aided in yak domestication by allowing the cross-breeding of wild yaks with cattle to produce a more tractable pack animal.

In arid lowland areas, the introduction of domestic sheep and goats most likely resulted in an increase in the frequency and duration of excursions by human groups into desert margins. This probably involved a shift in the dynamic relationship between full-time foragers, pastoralists, and nearby farmers, but beyond the notion of competitive exclusion, what this shift consisted of is unclear. Certainly by the later Holocene there is little evidence that any full-time foragers remained in these desert areas. As Madsen and Elston note, with the appearance of domestic camels, herdsmen began to fully exploit interior desert regions and this may have resulted in the final demise of foraging populations.

Tests of these models are conceptually simple, but practically difficult, as separating domestic animals from wild forms is, as Flad *et al.* note, notoriously difficult. If sheep pastoralism preceded yak domestication in the Tibetan Plateau margins, then stratified Neolithic sites of the appropriate age should demonstrate this sequence. Even should such sites be identified, however, they would need to contain sufficiently large collections of faunal remains that population profiles and size differences would allow the detection of wild versus domestic varieties. Most likely, we must await improvements in the extraction of DNA from fossil bone before many of these issues can be addressed.

4. Concluding Remarks

The papers in this volume provide a number of testable models exploring human adaptations to climate change during the Pleistocene/Holocene transition in arid China. Because of the focus on this transitional period, however, a number of important issues related to earlier and later periods received little attention. Principal among these is the question of when anatomically modern humans (AMH) appeared in arid China. Genetic data (e.g., Su *et al.*, 1999; Ke *et al.*, 2001) suggest such populations first appeared in the region about 50 ka as part of the general Out-of-Africa northward migration of AMH into Eurasia after 100 ka. Yet, archeological evidence suggests a smooth evolution of the core-and-blade industries that characterize the Early Upper Paleolithic of northern China and Mongolia beginning well before 70 ka (e.g., Brantingham *et al.*, 2001a; Gao and Norton, 2002; but see Dolukhanov *et al.*, 2002). Reconciliation of these two models requires either that AMH moving into the region immediately adopted the technology of their new Archaic Human neighbors or that the technology the AMH brought with them was identical to what they encountered as they entered the region. As these possibilities seem remote, either AMH populations entered China much earlier than current models suggest or changes in the sequence of lithic technologies remains to be discovered. The transition from the Middle to Upper Paleolithic (or "Early" to "Late" in the sequence of Gao and Norton (2002)) in China thus remains a fertile field of study.

Papers in this volume also paid little attention to human adaptation to climate change during the Late Neolithic to Historic periods. This is at least partially due to the volume's chronological scope, but also, as we noted in the introduction, it is because much of this research is available elsewhere. Intriguingly, what little is presented here on human/environmental interactions during the Late Holocene focus on possible human impacts on environmental change, not, as might be expected, the reverse. Zhao *et al.* briefly mention possible impacts settled village agricultural societies may have had on both the expansion of desert ecosystems and the decimation of forest cover, while Madsen and Elston provide a hypothetical model of how camel-based pastoralists may also have accelerated desertification. They suggest their model can be tested by comparing the rates at which desert margins expanded during similar climate change events before and after the appearance of domesticated camels. While positing similar tests is beyond the scope of the Zhao *et al.* chapter, it is likely such tests would also involve examining accelerated responses to climate change. As they note, however, it will first be necessary to eliminate climate as a causal agent of these accelerated changes, but chronological controls are as yet too coarse to make that determination. Such Late Holocene human-induced changes in arid China are most often attributed to the effects of agriculture and pastoralism on delicately balanced ecosystems, but human-set fire is also often seen as a causal agent (e.g., Huang *et al.*, 2006). While these effects are usually thought to be products of developed societies, they may also have been important during earlier periods, particularly in the semi-arid grasslands. Human-caused fires are thought to have been instrumental in major vegetation shifts in Australia as early as 45 ka (Miller *et al.*, 2005), for example, and the impacts of the forager use of fire during the Late Paleolithic and Early Neolithic in arid China have yet to be explored.

In summary, the papers in this volume suggest major abrupt climate change events have been critical elements in the Late Paleolithic to Neolithic transition in arid China. However, they also make it clear that the impacts of these events differed depending on the technological and social conditions in operation at any one time. The models that are offered to explain the relationships between these climate and cultural changes will surely be modified in the future, but without them, or others that replace them, we have little to guide us in our search for an increased understanding of that process.

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