of deep-sea sediments determined from short-lived and recently input radionuclides are generally $< 1\,\mathrm{cm}^2\ \mathrm{y}^{-1}$. (In shallow water sediments, mixing rates can be two orders of magnitude greater than observed in the deep sea.) The rate and depth of mixing of sediments determines the extent to which changes in paleoceanographic indicators (e.g., oxygen isotopes) can be resolved.

Long-lived radionuclides such as ^{10}Be offer the opportunity to extend radionuclide chronologies of deep-sea sediments to several million years. Recent advances in the measurement of ^{10}Be by accelerator mass spectrometry (AMS) permit analysis of small samples and high-quality chronologies to be determined using this radionuclide. Longer chronologies are especially useful in interpreting the record of parameters such as oxygen or carbon isotopes that are linked to paleoceanographic changes. Indeed it has become common to use the now well-established stratigraphy of oxygen isotopes to 'date' depth horizons of deep-sea sediments, yet it is important to recognize that the oxygen isotope stratigraphy was first established through the use of uranium series radionuclides (principally excess ^{230}Th).

Final mention must be made of the dating of horizons preserved in deep-sea sediments via the potassium–argon method. The method is based on the decay of ^{40}K (half-life $= 1.2 \times 10^9$ y) to stable ^{40}Ar, a noble gas. The method is useful only for materials whose initial argon was lost when the rock was formed. Subsequent production of ^{40}Ar in the rock is from ^{40}K decay and the ^{40}Ar/^{40}K ratio serves as an indicator of the rock's age. The method can be used to date volcanic materials that are deposited at the sediment–water interface, for example, as volcanic dust or ash associated with a volcanic eruption. Because of the long half-life of ^{40}K, this method has potential for dating sediments on long timescales, but because of the particular requirements (volcanic material deposited at the sediment–water interface), it is not often possible to use it.

See also

Cosmogenic Isotopes. Ocean Margin Sediments. Radiocarbon. Stable Carbon Isotope Variations in the Ocean. Temporal Variability of Particle Flux. Uranium–Thorium Decay Series in the Water Column. Uranium–Thorium Series Isotopes in the Ocean.

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SEDIMENTARY RECORD, RECONSTRUCTION OF PRODUCTIVITY FROM THE

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Introduction

Reconstruction of productivity patterns is of great interest because of important links of productivity to current patterns, mixing of water masses, wind stress, the global carbon cycle, hydrocarbon resources, and biogeography. The history of productivity is reflected in the flux of organic carbon into the sediment. There are a number of fluxes other than organic carbon that can be useful in assessing productivity fluctuations through time. Among others, fluxes of opal and of carbonate have been used, as well as the flux of particulate barite. In addition, microfossil assemblages contain clues to the intensity of production, as some species occur preferentially in high-productivity regions whereas others avoid these.

One marker for the fertility of subsurface waters (that is, for nutrient availability) is the carbon isotope ratio of totally dissolved inorganic carbon within that water ($^{13}C/^{12}C$, expressed as $\delta^{13}C$). In today's ocean, values of $\delta^{13}C$ of totally dissolved inorganic carbon are negatively correlated with nitrate and phosphate contents. Another useful tracer of phosphate content in subsurface waters is the Cd/Ca ratio. The correlation between this ratio and phosphate concentrations is quite well documented. A rather new development in the search for clues to ocean fertility is the analysis of the $^{15}N/^{14}N$ ratio in organic matter, which tracks nitrate utilization. The fractionation dynamics in the environment of growth are analogous to those of carbon isotopes. These various markers are captured within the organisms growing within the water tagged by the isotopic or elemental ratios.

Today's high production areas are in the temperate to high latitudes where wind-driven mixing is strong and where days are long in summer, and in equatorial and coastal upwelling regions (**Figures 1** and **2**). Favorable sites for burial of organic carbon are on the upper continental slope, not far off the coast where upwelling occurs, but far enough to reach depths of reasonably quiet water, where organic matter can settle and stay, embedded within silty sediment. The Pleistocene record in sediments on the continental slope shows large fluctuations in the burial rates of organic carbon which are generally interpreted as productivity fluctuations (unless redeposition from terrigenous sources is responsible).

Productivity Proxies

Organic Matter (and Oxygen Demand)

Generally speaking, there is a relationship between productivity in surface waters and organic carbon accumulation in underlying sediments. Below the central gyres (the deserts of the ocean) organic carbon content in sediments is extremely low. In upwelling areas, the organic carbon content is high, and in many cases sufficient for sulfate reduction and pyrite formation. From this observation, it may be expected that at any one place a change in the content of organic carbon indicates a change in productivity through time.

The range of variation in productivity of surface water spans roughly a factor of 10 (excluding estuaries and inner shelf), while the content in sediments varies by, for example, a factor of 40. The transfer of carbon from the surface waters to the sediments depends on the leakage of carbon out of the pelagic food web and the associated downward transport of organic matter, both in particulate and in dissolved

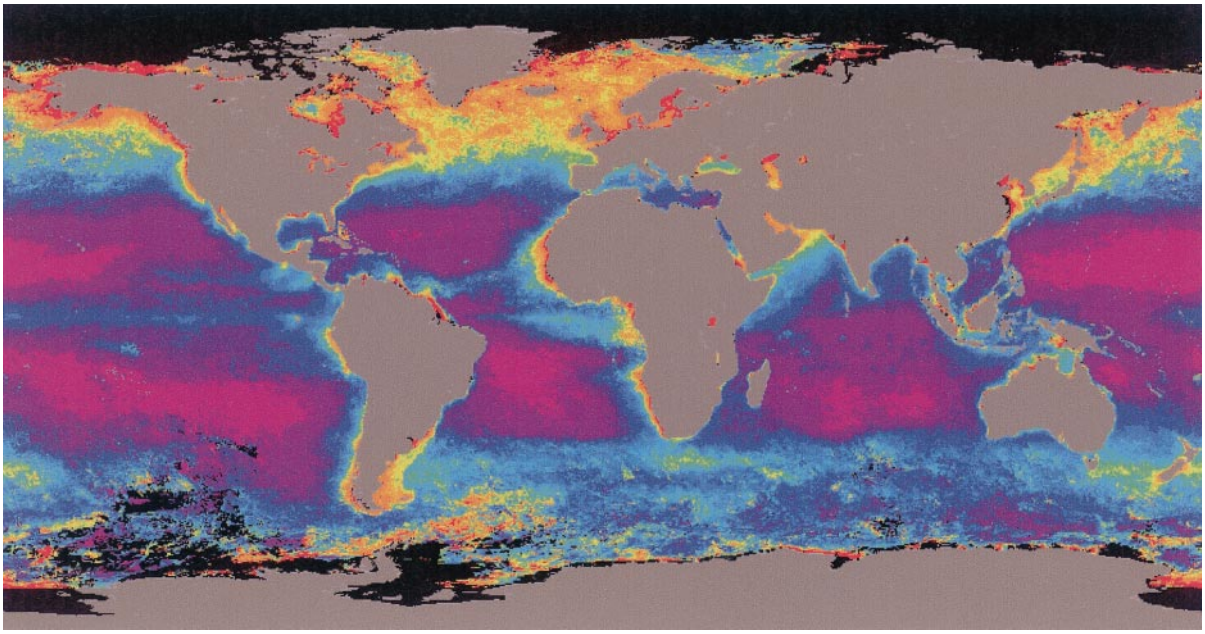

Figure 1 Pigment distribution in surface waters, inferred from color scanning data aboard C7CS satellite (November 1978–June 1986). Orange, high productivity ($> 150\,g\,C\,m^{-2}\,y^{-1}$); deep blue: low productivity ($50\,g\,C\,m^{-2}\,y^{-1}$). Sources: NASA/Goddard Space Flight Center, MD, USA, compiled by B. Davenport, Bremen.)

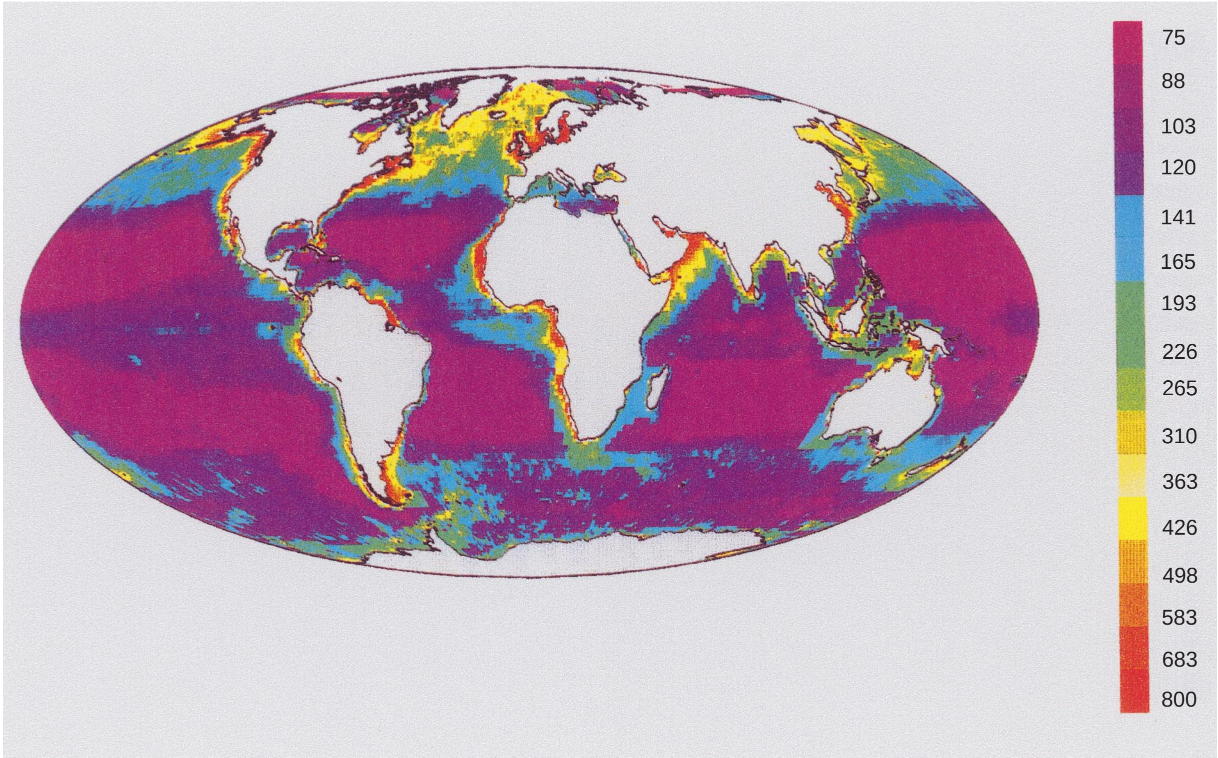

Figure 2 Primary production in grams carbon per m^2 and year, estimated from satellite radiometer data. (Reproduced with permission from Longhurst *et al.*, 1995.)

form. Favourable sites for burial of organic carbon are on the upper continental slope, for several reasons. The coastal setting results in high productivity, the shelf provides additional carbon, and setting and decomposition in the water column are of short duration.

The equation relating productivity (PP) to C_{org} content is of the form:

$$PP(a)/PP(b) = [C_{org}(a)/C_{org}(b)]^q$$

where q is usually between 0.6 and 0.8. Taking $C_{org}(b)$ as the Holocene standard value, the ratios downcore, after exponentiation to 0.7, are a reasonable estimate of the stratigraphic sequence of the factors of change of productivity. The great precision suggested by more complicated formulations must be largely doubted, especially since the influx of organic material redeposited from the shelves in regions close to continental margins can materially influence results.

The quantitative reconstruction of productivity from organic matter content was introduced just over 20 years ago, by P. Müller and collaborators. This work established that glacial periods showed higher productivity in the eastern North Atlantic than interglacial ones (**Figure 3**). Similar findings were subsequently made for the eastern and western equatorial Pacific and for the upwelling areas which depend on trade wind stress to power them.

Within the sediment, C_{org} is constantly being destroyed by bacteria. This is especially true close to the seafloor, but it is also evident several meters below. The destruction first proceeds by using free oxygen, but subsequently occurs by the reduction of nitrate, manganese oxide, iron oxide, and dissolved sulfate. The latter leads to precipitation of iron sulfide. Thus, an oxygen debt is built up within the sediment. Instead of using C_{org} as a productivity indicator (which results in a general trend for lower estimates with increasing age of sediment) it is reasonable to substitute oxygen demand (reducing power) as a proxy.

Opal (Mobile Silica)

A number of biologically derived substances other than organic carbon can also be useful in assessing productivity fluctuations. There is a good correlation in the flux of organic carbon and of carbonate in the open ocean, as seen in sediment traps. However, carbonate is commonly readily dissolved in sediments accumulating below areas of high production, during early diagenesis. Unlike carbonate, opal content is high in sediments below high productivity

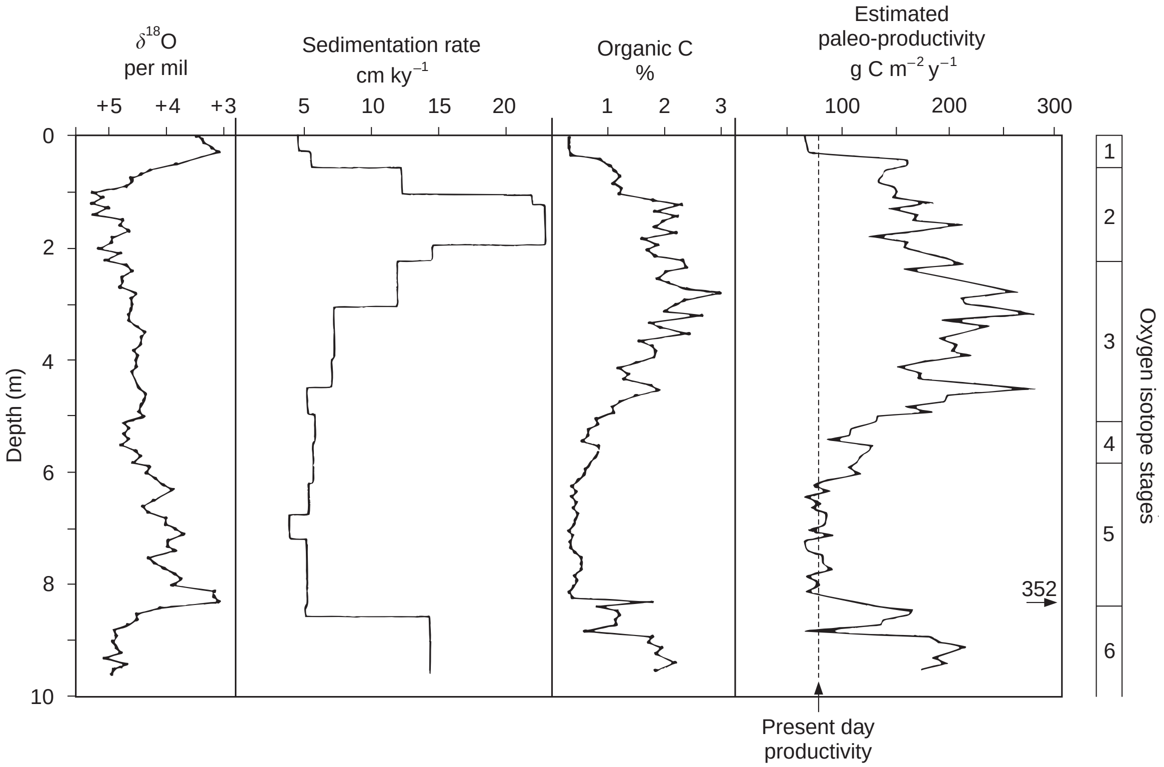

Figure 3 Paleo-productivity estimates for Meteor Core 12392–1 on the continental rise off the Spanish Sahara, north-west Africa. Sedimentation rate and organic carbon content are input variables from which productivity is calculated. Even numbers represent glacials and uneven numbers represent interglacials. (Reproduced with permission from Müller and Suess 1979 and Müller *et al.*, 1983.)

regions (e.g. in coastal upwelling regions), and low elsewhere (e.g. in oligotrophic areas). Its flux (as seen in traps) is well-correlated with that of C_{org}, the ratio of opal to C_{org} being especially high around the Antarctic.

Opal is originally brought into the sediment by the deposition of the skeletons of diatoms, radiolarians, and silicoflagellates, but has a tendency to migrate, especially in older sediments. Well over one half of the ocean's opal flux is concentrated in the Southern Ocean, where diatomaceous ooze accumulates over extensive regions. This reflects above all the high diatom productivity resulting from very deep mixing (which brings silicate to the photic zone) and from seasonal contrast (diatom blooms during onset of warming and stratification). The great efficiency with which silica is extracted from the ocean around the Antarctic continent implies that the overall concentration of silicate in the world ocean will depend to a large extent on changes in this efficiency through time. The state of the North Atlantic (which exports silica at present, North Atlantic Deep Water production being vigorous) also is important in setting the background level, as is the intensity of coastal upwelling and equatorial upwelling. Focused upwelling, by providing a smaller region from which to redissolve silica on the seafloor, has the effect of decreasing overall silicate concentrations. This effect has increased, overall, since the end of the Eocene period (Auversian Facies Shift, about 40 Ma) and has led to an overall removal of silica from deep-sea deposits (in favor of deposits in the ocean margins and in eastern equatorial regions).

Along the equator in the Pacific (and also to some extent in the Atlantic) the content of opal in sediments is considerably greater in the east than in the west, because of the higher supply of diatoms in the east, which in turn depends on the supply of nutrients and silicate, brought east by subsurface currents. In contrast, the western regions have rather thick warm-water layers which are depleted in nutrients. Quaternary changes in opal deposition in east and west are not in phase, presumably because of this strong element of asymmetry. The east–west contrast in opal sedimentation in the equatorial Pacific is much greater than the contrast in productivity. Thus, opal flux as a productivity index greatly amplifies the primary signal in this setting. Presumably, the cause of this amplification is that much of the silica is redissolved, not as a proportion of what is coming down, but as a background loss, which is largely independent of the amount of material delivered. This process has the effect of greatly increasing the initial differences in deposition. In the end, residuals which are chiefly composed of shells and shell fragments resistant to dissolution are compared. Such shells (that is, well-silicified large shells) are generated disproportionately in the more productive areas.

Because of the diatom-limiting nature of silicate concentrations opal is not a reliable proxy for productivity as such, but can only proxy for diatom production (as well as production of radiolarians and silicoflagellates). This is brought out well when studying the productivity record of the western equatorial Pacific. Here productivity increased by a factor near 1.5 over the present, during glacial time as judged from other productivity proxies. Instead of a higher rate of deposition of opal, however, we see a decreased rate is seen. Out-of-phase relationships between opal deposition and other productivity proxies are also known from deposits off south-western Africa, and from sediments in the Santa Barbara Basin and from off Peru. Clues to possible causes for these discrepancies may be found in the contrast of diatom sedimentation between equatorial Pacific and equatorial Atlantic. At the same level of productivity, opaline sediments are notoriously less in evidence in the Atlantic than in the Pacific Ocean, presumably due to a weaker silicification of diatom tests in the Atlantic. The cause of the asymmetry is taken to be the lower concentration of silicate in subsurface waters of the Atlantic, compared with those in the Pacific. Apparently, the glacial northern and central Pacific was more like the northern and central Atlantic today, i.e. there was much less silicate dissolved in its intermediate waters. This proposition agrees well with the other observations suggesting more ‘Atlantic’ conditions in the glacial Pacific, including the carbonate record (lowered carbonate compensation depth).

Isotope Ratios in Carbon and Nitrogen

In the reconstruction of productivity it is important to distinguish between flux proxies (which tag the export of biogenic materials from the surface to the seafloor) and nutrient proxies (which contain information about the nutrient content of the water wherein the production takes place). Isotopic ratios of carbon and nitrogen (expressed as deviation from a standard ratio, $\delta^{13}C$, $\delta^{15}N$) are nutrient proxies. The classical marker for the fertility of subsurface waters (i.e. the nutrients potentially available through mixing) is the difference in $\delta^{13}C$ values of surface waters and subsurface waters (it is usually given as $\Delta\delta^{13}C$), as seen in shallow-living and deep-living planktonic foraminifers. In the deeper waters, $\delta^{13}C$ decreases as nutrient contents rise, because the oxidation of organic matter within the thermocline sets free both carbon (with an excess content of ^{12}C) and the nutrients nitrate and phosphate. When the nutrient-rich deeper waters are brought to the surface, the $\delta^{13}C$ increases, because ^{12}C is extracted preferentially into organic matter and sinks with the excess production. The process continues until the nutrients are used up. Thus, the nutrient-free water retains a memory of former nutrient content through the anomalous enrichment in ^{13}C, over background. Unfortunately, the background is not usually well known, since the water is reset by exchange with the atmosphere and, on long timescales, by exchange with large carbon reservoirs. Hence the use of differences in $\delta^{13}C$: the larger the difference, the higher the nutrient content of the thermocline water.

In analogy to the difference in $\delta^{13}C$ between surface water and subsurface water the seasonal difference can also be used, providing that productivity is strongly pulsed, and thus samples the differing conditions of shallow and deep waters. Other differences are that between planktonic and benthic species (comparing surface water conditions with the deep ocean in general), and differences between benthic species living on or in the sediment, which provide clues to the $\delta^{13}C$ gradient between seafloor and interstitial waters within the uppermost sediment. This latter difference is expected to increase as the interstitial waters lose oxygen to the bacterial combustion of the organic matter.

A new tool in the reconstruction of productivity-related conditions is the use of the stable isotopes of nitrogen in organic matter, that is, the ratio of $^{15}N/^{14}N$ (expressed as $\delta^{15}N$). Assimilation of nitrate by phytoplankton is accompanied by nitrogen-isotope fractionation and produces a strong gradient in $\delta^{15}N$ as the source nitrate is consumed (with ^{15}N preferentially left behind) and organic matter is exported from the photic zone (with nitrate set free at depth, now enriched in ^{14}N). As a result of these processes, temporal and spatial changes in the balance between nitrate advection and consumption in the upper water layers will lead to corresponding changes in the $\delta^{15}N$ values of particulate nitrogen settling out of the productive zone and moving to the seafloor.

Elemental Ratios (Cd/Ca) and Trace Elements (Ba)

Many rare metals act as nutrients, that is, they are depleted in surface waters and enriched within

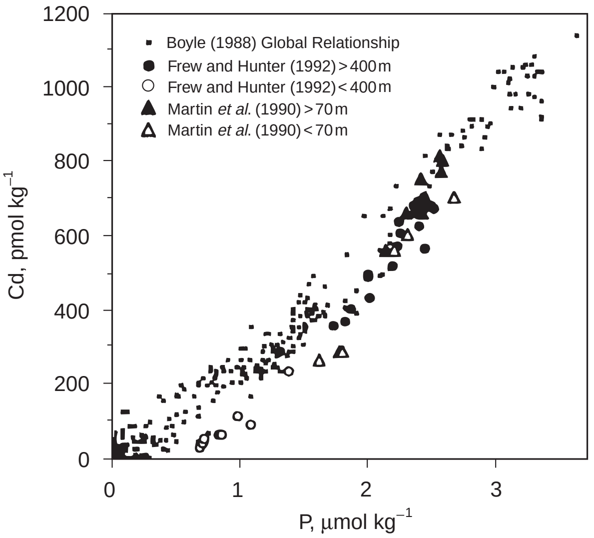

Figure 4 Correlations between Cd and phosphate in the open ocean below the mixed layer. (Adapted with permission from Boyle 1994.)

thermocline waters and at depth. If such elements are incorporated into organic matter or shells, their abundance can provide clues to the intensity of upwelling or the general level of concentration in upwelled waters, or both. Prime examples are the cadmium/calcium ratio in calcareous shells and the deposition of barium, which persists as barite (barium sulfate) within the sediment.

The Cd/Ca ratio was introduced by E. Boyle, in the 1980s, as a tracer of phosphate content in ocean waters. The correlation between the metal ratio and the nutrient content is remarkably good (**Figure 4**). It rests on the fact that cadmium is rare in sea water and tends to be extracted from surface water together with phosphate, being liberated again in deeper waters, upon oxidation of the organic matter binding it. Thus, cadmium and phosphorus are precipitated and redissolved together. Difficulties arise from the requirements of unusually demanding chemical procedures when extracting cadmium from shells in the seafloor (to avoid contamination) and from the possibility that correlations may not be stable through geologic time. The sources of sinks of cadmium, calcium, and phosphorus are all different. For example, cadmium tends to be precipitated as sulfide in anaerobic conditions. Thus, whenever anaerobic conditions expand (as perhaps during certain phases of the glacial–interglacial cycle) there will be a tendency for increased extraction of this element. When used as a proxy for phosphate, then, indications for phosphate would be lowered during times of poor deep-water ventilation, independently of the true phosphate content. Nevertheless, the method has proved useful as a tracer of deep-water phosphate content, as recorded in the shells of benthic foraminifers, for any one time period.

Barite has long been recognized as an indicator of productivity. For example, E. Goldberg and G. Arrhenius, in the 1950s, documented a distinct peak of barite accumulation below the equatorial upwelling region in the eastern Pacific, in a north-to-south transect. Compared with other paleo-productivity proxies such as organic matter, barite is quite refractory. It is not clear exactly how barium enters the export flux. In low latitudes, it may be surmised that incorporation into skeletons by acantharians (Radiolaria), and subsequent precipitation as microcrystals of barite within sinking aggregates, is important. Elsewhere, diatom flux and organic matter flux presumably bring the barium with them. In any case, changing barite abundances agree well with productivity fluctuations on glacial–interglacial timescales.

Barite, as a flux proxy, is subject to variations in availability, much like opal. Therefore it may not be a ‘pure’ indicator of productivity. Problems arise especially when the record is contaminated by terrigenous barite particles. In addition, small changes in oxygen concentration, at sensitive levels, can influence the abundance of sulfate ions in interstitial waters and hence the stability of microscopic barite crystals.

Microfossil Assemblages

Within each group of planktonic organisms, some species occur preferentially in high-productivity regions while others avoid these, or cannot compete in bloom situations. Thus, among the shelled plankton, the relative abundances in the sediment contain clues to the intensity of production at the time of sedimentation.

Microfossil assemblages will have aspects of flux proxies but also reflect ecologically important conditions such as sequences of mixing and stratification, or seasonality in general. Among the proxies for flux are the diatom species directly involved in upwelling blooms, such as *Chaetoceros*. In addition, there are more subtle changes in species composition that reflect differences in the style and intensity of mixing and production. In the eastern equatorial Atlantic, for example, changes have been found in the diatom flora that indicate increased productivity during glacial time.

Among planktonic foraminifers, a number of species have been identified as indicators of high productivity. In low latitudes, for example, these include the forms *Globigerina bulloides, Neogloboquadrina dutertrei,* and *Globorotalia tumida.* In temperate latitudes, *Globigerina quinqueloba* is

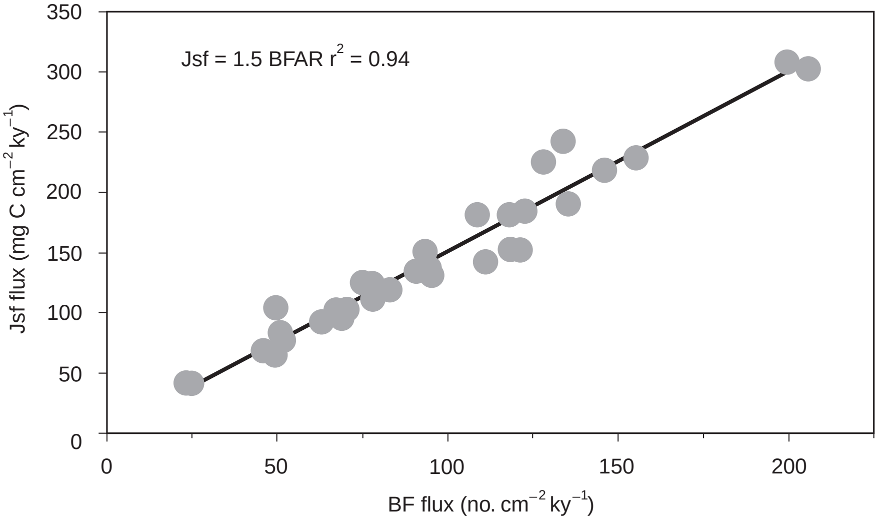

Figure 5 Benthic foraminifera accumulation rate (BFAR) and flux of organic matter to the seafloor (Jsf). Data based on box-core data from eastern and western equatorial Pacific, and from South Atlantic, as given in Table 1, Herguera and Berger, 1991. The graph compares core-top data with productivity estimates (PP) based on the map in Berger *et al.* (1989). Jsf is taken as $0.25 \cdot PP^2/Z + 0.5 \cdot PP/Z^{0.5}$ and from this relationship PP can be estimated from BFAR, by solving for PP. Z is water depth.

useful as a productivity indicator, while *N. pachyderma* (sin.) indicates very cold upwelling water. Thus, the ratio of these species to their more warm-loving contemporaries should provide good indicators of upwelling. Multivariate statistics that use relative abundance of species yield interesting results. In some cases, results from different reconstructions (e.g. organic carbon versus microfauna) differ considerably. The reasons are poorly understood as yet.

Benthic foraminifers live on the organic material falling to the seafloor. Thus, their abundance should vary with the food supply from above. This is indeed the case, as shown by comparing the accumulation of benthic foraminifers with the overlying productivity for various regions (see **Figure 5**). As the food supply changes, the chemical conditions on the seafloor also change, and therefore the bacterial flora is affected. In turn, this must influence the composition of the benthic fauna. Indeed, the open-ocean faunas (where food may be presumed to be in short supply) are dominated by *Cibicidoides, Eponides, Melonis, Oridorsalis*, and others, while the faunas below the productive upwelling regions along the continental margins are dominated by *Uvigerina, Bolivina, Bulimina*, and associated forms. Various observations suggest that it will be difficult to use species composition in benthic foraminifers as productivity indicators, within high production regions. Other factors besides productivity (oxygen deficiency, sulfide abundance) may be more important at high levels of organic matter flux. However, at low to intermediate levels of productivity faunal changes should be readily detectable.

Examples for Productivity Reconstructions

Equatorial Upwelling

One of the earliest attempts at quantitative reconstruction of equatorial upwelling was carried out by G.O.S. Arrhenius, working with sediments from the eastern equatorial Pacific, raised by the Swedish Deep-Sea Expedition. He used changes in the size distribution of diatoms to argue for greatly increased productivity during glacial periods, which he related to increased upwelling from increased trade wind stress. These suggestions have been fully confirmed, most recently by the study of barite deposition see **Figure 6A**). The results show a strong precessional cycle, as expected if wind is the driving force. (Winds are influenced both by the overall planetary temperature gradient, which greatly increases during glacial periods as the northern polar front migrates toward the equator, and by the intensity of the summer monsoon which varies on a precessional cycle.)

Interestingly, the western equatorial Pacific shows a quite similar pattern, as seen in the oxygen demand data (see **Figure 6B**). Again, the precessional signal is quite strong. These results likewise confirm earlier studies showing increased glacial productivity in this region. (For the eastern part, the factor of change is thought to be somewhat greater than in

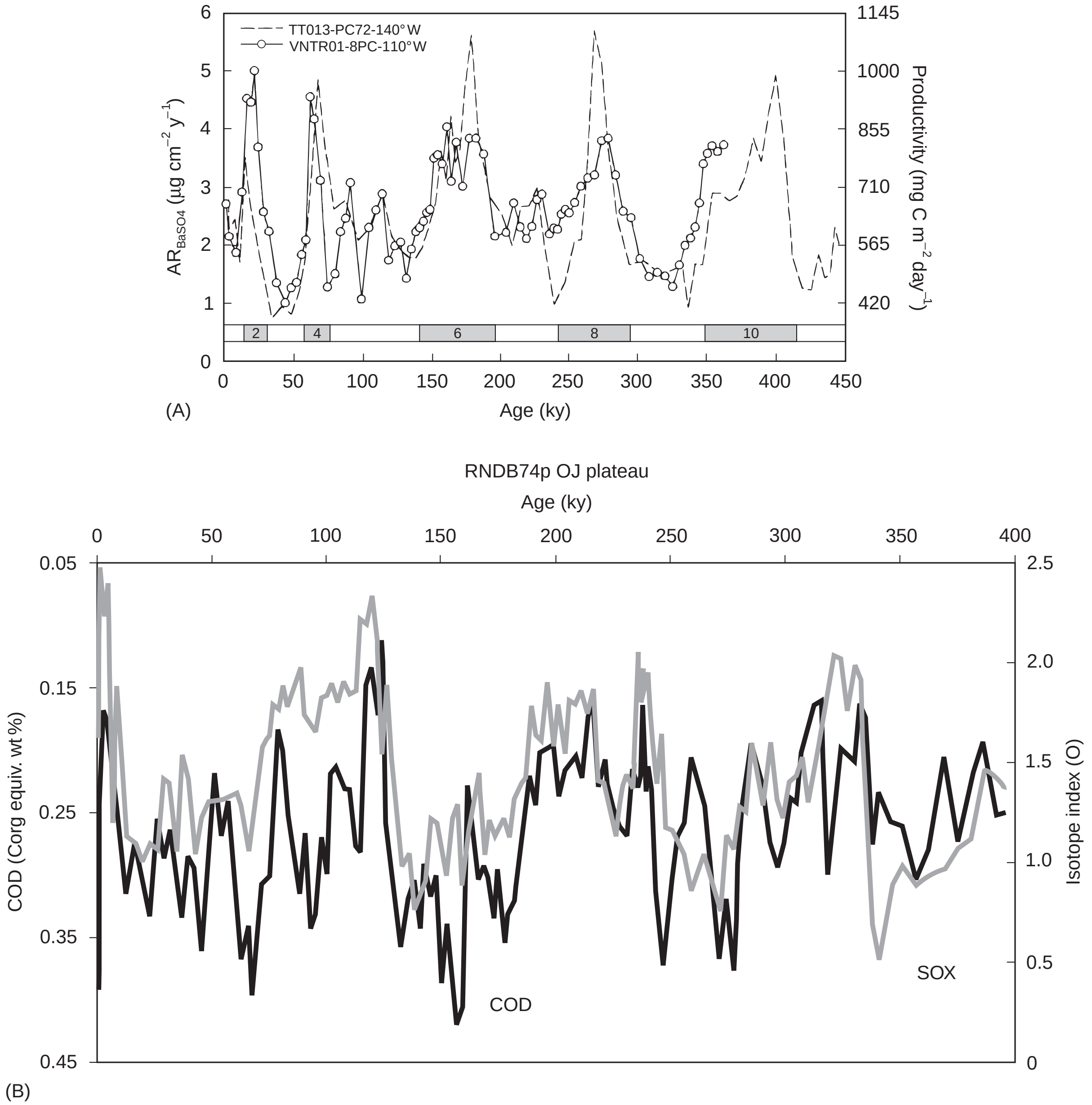

Figure 6 Productivity history in the equatorial Pacific. (A) Accumulation rate of barite (AR_{BaSO_4}) and productivity in the central and eastern equatorial Pacific (Reproduced with permission from Kastner, 1999.) Even numbers represent interglacials and uneven numbers represent glacials. (B) Oxygen demand in the western equatorial Pacific Ontong Java Plateau (Oxygen isotope data core RNDB 74P reproduced with permission from Perks, 1999. COD, organic carbon demand; SOX, oxygen isotope index. Data from Ontong Java Plateau 0°, 20.48°N, 159°22.49°E, 2547 m depth, reproduced with permission from Yasuda and Berger (unpublished observation).

the west, for example, about 2 in the east, and around 1.5 in the west, for the glacial-to-interglacial contrast.) As mentioned, the opal deposition does not reflect this general pattern. While varying in phase with glacial–interglacial conditions in the east (similar to organic matter and barite) it varies at counterpoint phase in the west. Therefore a strongly decreased silicate content in thermocline waters in the west is indicated. In the present ocean, low silicate values go parallel with decreased phosphate values (with the silicate decreasing much faster than the phosphate). Therefore it is likely that the phosphate content of intermediate waters was decreased over large parts of the central Pacific, during glacial time. Thus the increased productivity in the western equatorial Pacific has to be the result of very vigorous mixing, and not of increased nutrient concentrations.

In the Atlantic, also, equatorial upwelling increased during glacial times, especially in the eastern regions (see Further Reading section: particularly, Berger and Herguera, 1992 and Wefer *et al*., 1996.

Coastal Upwelling Centers

The increase in glacial productivity off north-west Africa has been mentioned (**Figure 3**); it is well established and has been confirmed many times. Much information has recently become available from off the coast of central and southern Africa. Off the mouth of the Congo River, productivity was high during glacials and low during interglacial stages, as a rule; the maximum range suggested by the data exceeds a factor of three (**Figure 7A**), certainly for the contrast between the last glacial and the late Holocene stages. A precessional influence seems quite strong. The enormous accumulation of organic matter and the correspondingly high accumulation in opal during the last glacial maximum are noteworthy. The lack of response to the Stage 4 glacial is puzzling. A comparison core is needed to exclude the possibility of missing material.

Off Angola the fluctuations in the rates of carbon accumulation are comparable to those off the Congo River (**Figure 7B**). However, the opal accumulation is rather insensitive to the variation in productivity seen in the C_{org}. As for the western equatorial Pacific, relatively low silicate values must be postulated for glacial periods, which in essence compensate for the increase in upwelling. By the above argument (phosphate decreases with silicate but at a lesser rate) the nutrient content of water welling up during glacial periods was less than during interglacials, but strong winds overcame the effect by producing much more vigorous mixing and upwelling than today.

Matuyama Opal Maximum off Southwestern Africa

The various caveats regarding productivity reconstruction which have been pointed out and illustrated make it extremely difficult to take quantitative reconstruction far into the past. Indeed for the more distant time periods (e.g. pre-Neogene) the sign of the change is not clear (mainly because lack of oxygen simulates many of the indicators of high production, and because of the unreliability of the opal record).

Recently, a concerted effort has been made by Leg 175 of the Ocean Drilling Program to attempt a comprehensive reconstruction of productivity of the Benguela upwelling system, for the late Neogene period. Results so far are both puzzling and enlightening. When contemplating opal deposition

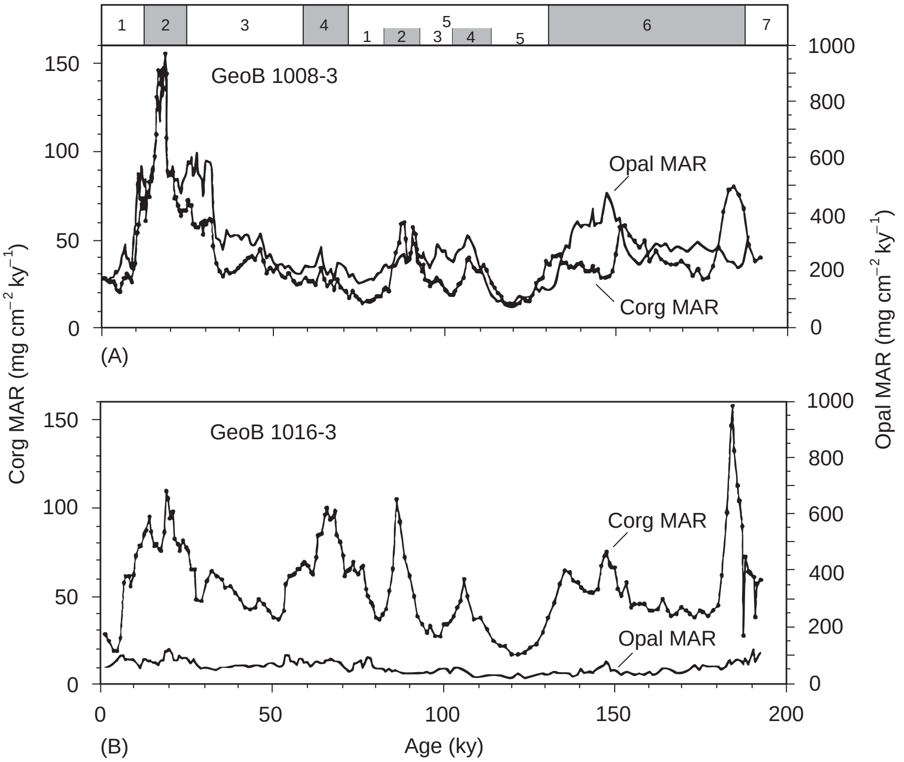

Figure 7 Accumulation rates of organic carbon and of opal in the South Atlantic. (A) Congo fan area. (B) Off Angola. Even numbers are glacial and uneven numbers are interglacial isotope stages. (Reproduced with permission from Schneider, 1991).

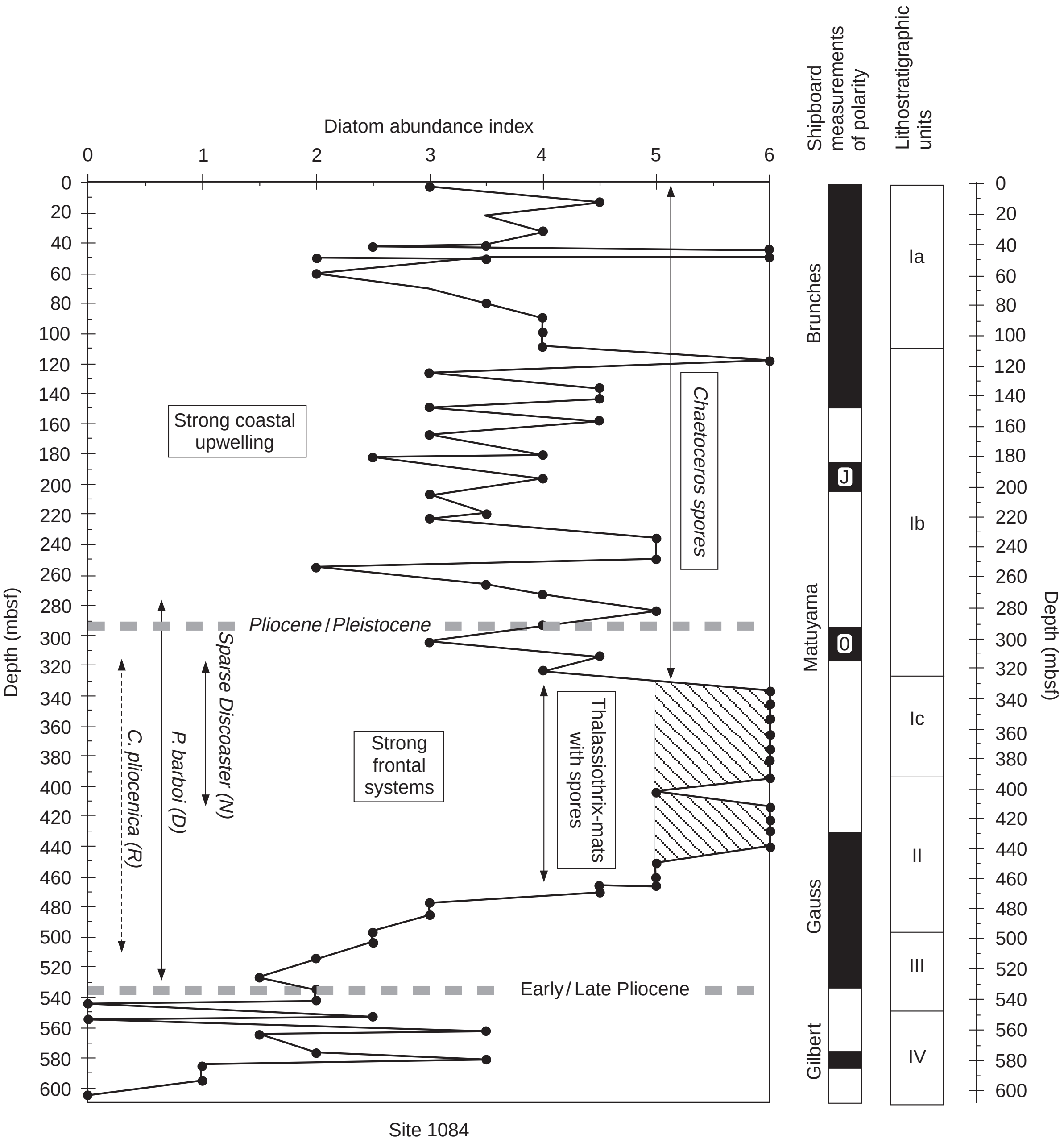

Figure 8 The Matuyama Diatom Maximum off south-western Africa, as seen in Hole 1084A. Shipboard measurements of polarity and lithographic units are given on the right-hand side. The time interval of subantarctic influence in the late Pliocene is exemplified by the presence of *Proboscia barboi* (diatom) and *Cycladophora pliocenica* and by the sparse occurrence of *Discoaster* nannofossil species. Strong coastal upwelling dominated over Site 1084 in the Pleistocene, whereas strong frontal systems (among the BCC (Benguela Coastal Current), the upwelling filaments, and the BOC (Benguela Oceanic Current) dominated the late Pliocene, as exemplified by *Chaetoceros* resting spores and Thalassiothrix-rich sediments, respectively. (Reproduced with permission from Wefer *et al.* (1998), as drawn by C.B. Lange.)

of the last 3 My, a rapid increase in deposition in the late Pliocene is found, and then an overall decrease to lower values as the system moves into the Quaternary and increased overall ice buildup. Parallel to the trend of decreasing opal deposition, there is, paradoxically, an increase in spores of the diatom *Chaetoceros*, indicating increased upwelling. The maximum itself, between 2.2 and 2.0 My, is characterized by a rich mixture of various diatom floras, including Antarctic, central ocean, and upwelling. Dense deposits of almost pure diatom ooze ('diatom mats') are also found in this portion, suggesting self-sedimenting blooms along major ocean frontal systems (**Figure 8**).

The peculiar stratigraphy of the Matuyama Diatom Maximum – maximum deposition of opal along a long-term trend of temperature decrease – emphasizes the presence of several competing factors as the climate moved into the northern ice ages. These include winds and eddy formation off southwestern Africa, access of Antarctic waters and waters from the Agulhas Current from the Indian Ocean, as well as intensity of coastal upwelling and the quality of the upwelling water. The overall message in terms of geochemistry is that the quality of the upwelling water suffered (i.e. nutrients decrease) as the world moved into the Quaternary ice ages. In principle, this agrees with the reverse opal deposition (with respect to other productivity indicators) observed within the glacial–interglacial themselves.

Conclusions

Various sediment properties deliver useful information for reconstructing past productivity of the ocean. Major improvements have been made in the attempt to understand productivity conditions in the past. Nevertheless, proxies require further calibration and testing with time-series and time-slices. Water samples, plankton nets, and sediment trap investigations, in conjunction with laboratory experiments, are of great importance in making these calibrations. It has to be taken into account that a single proxy is not sufficient to document productivity conditions, so a number of proxies should always be used (multiproxy approach).

See also

Conservative Elements. Nitrogen Isotopes in the Ocean.

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SEICHES

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Introduction

Seiches are resonant oscillations, or ‘normal modes’, of lakes and coastal waters; that is, they are standing waves with unique frequencies, ‘eigenfrequencies’, imposed by the dimensions of the basins in which they occur. For example, the basic behavior of a seiche in a rectangular basin is depicted in **Figure 1**. Each panel shows a snapshot of sea level and currents every quarter-period through one seiche cycle. Water moves back and forth across the basin in a periodic oscillation, alternately raising and lowering sea level at the basin sides. Sea level pivots about a ‘node’ in the middle of the basin at which the sea level never changes. Currents are maximum at the center (beneath the node) when the sea level is horizontal, and they vanish when the sea level is at its extremes.

Seiches can be excited by many diverse environmental phenomena such as seismic disturbances, internal and surface gravity waves (including other normal modes of adjoining basins), winds, and atmospheric pressure disturbances. Once excited, seiches are noticeable under ordinary conditions because of the periodic changes in water level or currents associated with them (**Figure 1**). At some locations and times, such sea-level oscillations and currents produce hazardous or even destructive conditions. Notable examples are the catastrophic seiches of Nagasaki Harbor in Japan that are locally known as ‘abiki’, and those of Ciutadella Harbor on Menorca Island in Spain, called ‘rissaga’. At both locations extreme seiche-produced sea-level oscillations greater than 3 m have been reported. Although seiches in most harbors do not reach such heights, the currents associated with them can still be dangerous, and for this reason the study of coastal and harbor seiches and their causes is of practical significance to harbor management and design. In this article we place emphasis on marine seiches, especially those in coastal and harbor waters.

History

In 1781, J. L. Lagrange found that the propagation velocity of a ‘long’ water wave (one whose wavelength is long compared to the water depth h) is given by $(gh)^{1/2}$, where g is gravitational acceleration. Merian showed in 1828 that such a wave, reflecting back and forth from the ends of a closed rectangular basin of length L, produces a standing wave with a period T, given by

$$T = \frac{2L}{n(gh)^{1/2}} \qquad [1]$$