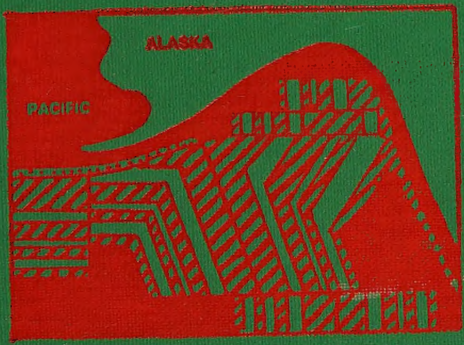
INNER EARTH: A SEARCH FOR ANOMALIES

Compiled by:

William R. Corliss



A CATALOG OF GEOLOGICAL ANOMALIES

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Published and Distributed by:

The Sourcebook Project P.O. Box 107 Glen Arm, MD 21057

Library of Congress Catalog Number: 90-92347

ISBN 0-915554-25-9

First printing: March 1991

Printed in the United States of America

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PREFACE

After more than twenty years of scouring the scientific and semiscientific literature for anomalies, my major conclusion is that this is a most fruitful activity. In fact, organized science should have been compiling such information over the past 200 years. It is surprising that a Catalog of Anomalies does not already exist to guide scientific thinking and research. It is at least as important to realize what is anomalous as it is to recognize the well-explained facts of nature. With this outlook, here is the eleventh volume of such a Catalog. It is largely the product of one person's library research, carried forward entirely through the sale of these Catalogs, Handbooks, Sourcebooks, and related books on anomalies.

Under the aegis of the Sourcebook Project, I have already published 27 volumes, totalling roughly 10,000 pages of source material on scientific anomalies. (See page iv for the list of titles.) As of this moment, these 27 volumes represent only about 40% of my data base. New material is being added at the rate of about 1,200 new items per year, about 500 of which come from the current scientific literature. These acquisition rates could easily be multiplied several-fold simply by spending more time in libraries. Even after twenty years, only the English-language scientific journals have received my serious attention. The journals in other languages, government reports, conference papers, publications of scientific research facilities, untold thousands of books, and an absolutely immense reservoir of newspapers remain almost untouched. Every library foray uncovers new scientific anomalies; the world's libraries are bulging with them.

Given this rough assessment of the magnitude of the anomaly literature, one can understand why the Catalog of Anomalies will require at least 25 volumes, many of them larger than the one you now hold. I visualize a shelf of these 25 volumes, with master indexes, to be only the initial step in providing scientists with ready access to what, in my opinion is not well-explained. The underlining of "my" is important because anomalousness is often in the eye of the beholder. It depends upon how well one is satisfied with explanations based upon currently popular theories. In the Catalog of Anomalies, the data rule; all theories and hypotheses are deemed tentative. The history of science demonstrates that this is a wise policy.

Will the Catalog of Anomalies revolutionize science? Probably not---at least not right away. Quite often the initial reaction to the volumes already published has been disbelief and even disdain. The data must be in error; the data are mainly testimonial; the data are too old; the purported anomaly was really explained long ago. Germs of truth reside in all these complaints. Some science and some observations are certainly bad. Also, the baseline of well-established theories, against which anomalousness is measured, is always shifting. But for every anomaly that can be legitimately demolished, a trip to the library will replace it with ten more from impeccable sources. In sum, Nature is very anomalous or, equivalently, Nature is not yet well-understood. Much remains to be done.

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March 1, 1991.

"ROUND ABOUT THE ACCREDITED AND ORDERLY FACTS OF EVERY SCIENCE THERE EVER FLOATS A SORT OF DUST-CLOUD OF EXCEPTIONAL OBSERVATIONS, OF OCCURRENCES MINUTE AND IRREGULAR AND SELDOM MET WITH, WHICH IT ALWAYS PROVES MORE EASY TO IGNORE THAN TO ATTEND TO . . . . ANYONE WILL RENOVATE HIS SCIENCE WHO WILL STEADILY LOOK AFTER THE IRREGULAR PHENOMENA. AND WHEN THE SCIENCE IS RENEWED, ITS NEW FORMULAS OFTEN HAVE MORE OF THE VOICE OF THE EXCEPTIONS IN THEM THAN OF WHAT WERE SUPPOSED TO BE THE RULES." William James.

HOW THE CATALOG IS ORGANIZED

Purpose of the Catalog

The Catalog of Anomalies is designed to collect and categorize all phenomena that cannot be explained readily by prevailing scientific theories. Following its definition, each Catalog anomaly is rated in terms of: (1) its substantiating data; and (2) the seriousness of the challenge the anomaly poses to mainstream scientific theories. Next, all examples of the anomaly discovered so far are recorded, some of the more interesting ones in more detail. Finally, all examined references are listed. Thus, the Catalog is a descriptive guide as well as a compendium of examples with supporting references. Scientific researchers thus have a substantial foundation for beginning further studies of these intriguing phenomena. This is the basic purpose of the Catalog: the collection and consolidation of the unknown and poorly explained in order to facilitate future research and explanation.

General Plan of the Catalog

It was tempting to organize this Catalog alphabetically, making it an "encyclopedia of anomalies". But many of the phenomena have obscure names or, even worse, no names at all. Under these circumstances, access to the data base would be difficult. Therefore, a system of classification was designed based upon readily recognized classes of phenomena and the means the observer uses to detect them. The universe of anomalies is first divided into nine general classes of scientific endeavor, as illustrated in the diagram on the following page. Few people would have difficulty classifying a phenomenon as biological, astronomical, geological, etc. The second, third, and fourth levels of classification are also based upon generally recognized attributes. The similarity of this kind of categorization to that employed in natural-history field guides is quite intentional. Like bird indentification, phenomenon classification soon becomes second nature. In fact, many of the phenomena described in this Catalog are accessible to anyone with normal senses and, especially in astronomy, a little optical help.

Most catalogs employ numbering systems, and this one is no exception. Rather than use a purely numerical system, the first three levels of classification are designated by letters. The triplets of letters selected have some mnemonic value. Thus, an EZP anomaly is easily recognized as belonging to the geology class (E), involving the earth's magnetic field (Z), and concerning paleomagnetism (P). The number added to the triplet of letters marks the fourth classification level, so that EZP5 denotes correlations between paleomagnetic excursions or reversals with other geophysical phenomena, such as biological extinctions, as indicated in the diagram. Every type of anomaly has such a unique alphanumeric code. All cross references and indexes are based on this system. Catalog additions and revisions are also made easier with this approach.

The Catalog codes may seem cumbersome at first, but their mnemonic value to the compiler has been considerable. The codes are simple, yet they are flexible enough to encompass the several thousand types of anomalies identified so far in diverse scientific disciplines.

A glance through this volume will reveal that each example of an anomaly type bears an X-number, and each reference an R-number. EZP5-X2 therefore specifies the second example of paleomagnetic excursions correlated with other geophysical phenomena. EZP5-R5 is the fifth reference in the phenomenon's bibliography.

How Data and Anomalies Are Evaluated

Each anomaly type is rated twice on four-level scales for data "validity" and "anomalousness", as defined below. These evaluations represent only the opinion of the compiler and must be considered only rough guides.

Data Evaluation Scale

1 Many high-quality observations. Almost certainly a real phenomenon.

2 Several good observations or one or two high-quality observations. Probably real.

3 Only a few observations, some of doubtful quality. Phenomenon questionable.

4 Unacceptable, poor-quality data. Such entries are included only for purposes of comparison and amplification.

Anomaly Evaluation Scale

1 Anomaly cannot be explained by modifications of present laws. Revolutionary.

2 Can probably be explained through relatively minor modifications of present scientific laws.

3 Can probably be explained using currently popular theories. Primarily of curiosity value.

4 Well-explained. Included only for purposes of comparison and amplification.

First-order classification	Second-order classification	Third-order classification	Fourth-order classification
A Astronomy	C Geochemistry & physics	C Field perturbations	1 Measurement & interpretation
B Biology	Q Seismology	F Configuration & secular variation	2 Excursions & reversals
C Chemistry & Physics	S Stratigraphy	(P) Paleomagnetism	3 Paleopoles
			4 Inconsistencies
(E) Earth sciences	T Topography		
G Geophysics	(Z) Magnetism		(5) Correlations with other phenomena
L Logic & math			
M Archeology			
P Psychology			
X Unclassified			

Catalog Coding Scheme

Referring to the evaluation scales on the opposite page, it should be remarked that anomalies that rate "1" on both scales are very rare. Such anomalies, however, are the most important because of their potential for forcing scientific revolutions.

Anomaly Examples

Examples of anomaly types are designated by the letter X in the body of the Catalog. All examples discovered so far are entered, except in the cases of extremely common phenomena, such as ball lightning. If the example is of the event type, time and place are specified where available. Such data are the basis of the Time-of-Event and Place Indexes, which could in principle lead to the discovery of obscure cause-and-effect relationships. Where library research has unearthed many examples of a specific type of anomaly, only the more interesting and instructive are treated in detail. Direct quotations from eye-witnesses and scientific experts are employed frequently in order to convey accurately the characteristics of the phenomenon.

The References and Sources

Each anomaly type and the examples of it are buttressed by all references that have been collected and examined. Since some references deal with several examples, each reference includes the X-numbers of the examples mentioned. When a reference covers more than one type of anomaly, it is repeated in each anomaly bibliography. Actually, there is little repetition of this sort in the Catalog.

Perusal of the Source Index will demonstrate that the great majority of the references employed comes from the scientific literature. Heavily represented in this volume of the Catalog are such journals as: Nature, Journal of Geology, Science, and the Bulletin of the Geological Society of America. Some less technical publications are also used frequently, such as Science News and New Scientist. All of the serials just mentioned are generally very reliable, although one must always be wary when dealing with unusual phenomena. In addition to these often-referenced publications, there is a wide spectrum of other journals that carry geological data. Since many geological phenomena are easily observed, useful observations may be found almost anywhere.

The sources employed date from the beginning of organized science some 200 years ago. The great bulk of the data, however, come from the past 80 years. In particular, the data from marine geology and geomagnetism are of very recent vintage. Indeed, advances are being made so rapidly in geology and geophysics that some things in the volume will be outdated before the books leave the bindery.

The Indexes

Most Catalog volumes conclude with five separate indexes. At first glance this may seem to be too much of a good thing. But in the context of a science-wide Catalog of Anomalies, each index helps tie the whole together.

The Subject Index is of course essential for anomaly research. It is placed at the end of the book for easy access. The Time and Place Indexes are analytical tools for the anomalist, for they help connect diverse phenomena that are often reported separately in different journals. To illustrate, meteoritic phenomena are to be found in those Catalog volumes covering astronomy, geology, geophysics, archeology, and even in biology, where the subject of mass extinctions arises. It is the purpose of the Catalog indexes to tie together all of the nine categories of scientific endeavor tabulated earlier.

How the Catalog Is Organized

The Source Index shows immediately the dependence of this Catalog upon the scientific literature rather than newspapers and other popular publications. Its real purpose, though, is the rapid checking of newly acquired references to determine whether they have already been caught in the fishing net of the library-research aspect of the Catalog effort. The Source Index is doubly valuable because many footnotes and bibliographies in the scientific literature omit article titles and, sometimes, even authors! The researcher also comes across vague references to such-and-such an article by so-and-so back in 1950 in Nature. In such cases, the rather ponderous Source and First-Author Indexes can help pin down references lacking in specifics.

The five indexes use the Catalog codes described above rather than page numbers. The codes are permanent whereas page numbers would change as volumes are revised. The mnemonic value of the Catalog codes is evident here, too, because the approximate nature of each index entry is readily apparent, while page numbers provide only location.

Supporting Publications of the Sourcebook Project

The Catalog volumes currently being published are actually distillations of huge quantities of source material. The Sourcebook Project has already published 27 volumes of such material, as detailed on p. iv. Phase I of the Sourcebook Project resulted in ten looseleaf notebooks called "sourcebooks". To meet the demands of libraries, Phase II supplanted the sourcebooks with a series of six "handbooks", which are casebound, much larger, and more comprehensive than the sourcebooks. Phase III, now in progress, is the cataloging phase. This consists of systematizing the data base, which now comprises some 35,000 articles, and the publication of the "catalogs".

Catalog Addenda and Revisions

Over 1200 new reports of anomalies are collected each year from current and older scientific journals. New anomaly types and additional examples of types already cataloged are accumulating rapidly. When sufficient new material has been assembled, Catalog volumes will be revised and expanded.

The Sourcebook Project welcomes reports of scientific anomalies not already registered in extant Catalog volumes. Reports from scientific journals are preferred, but everything is grist for the anomaly mill! Credit will be given to submitters in new and revised Catalog volumes. If the reports are from current literature they may be mentioned in Science Frontiers, the Project's newsletter. Send data to: Sourcebook Project, P.O. Box 107, Glen Arm, MD 21057.

INTRODUCTION

The present volume of the Catalog of Anomalies concludes the four-volume compilation of "geological anomalies". There remains, of course, much unexamined literature containing still more geological anomalies. In the future, an expansion and refinement of these four volumes will be essential. They represent only a beginning, and a somewhat naive one at that.

The focus here is "inner earth", the core, mantle, and deeper crust, mainly as revealed by seismology and the structure and behavior of the geomagnetic field. Other pertinent areas of research recognized herein are gravimetry, heat-flow analysis, and geochemistry. Unfortunately, our data collection for these latter fields is thin in terms of quantity. Future editions will correct this deficiency.

Added to the "inner earth" theme in this volume is a chapter dealing with larger. often planet-spanning aspects of stratigraphy, such as: large overthrusts, large-area cyclothems, and the great greenstone belts. Such subjects are certainly a part of "surface geology" but inner-earth forces have contributed significantly to their genesis.

Although our Catalog of Geological Anomalies will never be complete, its four volumes, plus three volumes from astronomy, and four from geophysics form a good foundation upon which to begin the Catalog of Biological Anomalies. In the "biology" volumes there will be found many connections to geology (biological extinctions), astronomy (possible cometary origin of biological materials), and geophysics (animal detection of earthquake precursors). There is not one volume in the Catalog of Anomalies that does not impinge upon every other volume in some way.

EC MISCELLANEOUS CHEMICAL AND PHYSICAL ANOMALIES ASSOCIATED WITH INNER EARTH

Key to Categories

ECC CHEMICAL ANOMALIES ASSOCIATED WITH INNER EARTH
ECD SURPRISING DISCOVERIES FROM DEEP DRILLING
ECG STRUCTURAL ANOMALIES INDICATED BY GRAVITATIONAL ANOMALIES
ECH HEAT-FLOW ANOMALIES

The purpose of this short chapter is the collection of chemical and physical anomalies that are not treated separately under EQ (seismological anomalies) and EZ (geomagnetic anomalies). In principle, the four categories keyed above (ECC, ECD, ECG, ECH) could stand as separate chapters, but our literature research in these areas has lagged. We hope to rectify this oversight in future editions of the Catalog of Anomalies.

Despite the above deficiency, our picture of inner earth is considerably enhanced by studying the gases emanating from deep in the mantle and the distribution of internal heat reaching the crust's surface. Most surprising of all have been the discoveries of scientific deep-drilling programs. The crust is hotter and wetter than anyone had expected, and structures sketched from seismological and gravitational observations have sometimes turned out to be something quite different indeed. If we could only drill into the mantle, even greater surprises would be uncovered, we are certain.

ECC CHEMICAL ANOMALIES ASSOCIATED WITH INNER EARTH

Key to Phenomena

ECC0 Introduction

The purpose of this section is the highlighting of chemical anomalies that seem to reflect upon the origin, evolution, and constitution of the earth-as-a-whole. So far, only some of the noble gases appear to meet these criteria. Further research will doubtless uncover more candidates.

This section is closely related to the release of radon and methane from the earth's crust. (ESC15, ESC16) Since the emanations of these two gases are considered to be primarily crustal phenomena, they are classified in ESC, which is located in the Catalog volume entitled Anomalies in Geology.

ECC1 The Anomalous Abundances of Some Noble Gases

Description. Abundances of noble gases that are either too high or too low in reference to the accepted theories of origin for the earth and the evolution of its core, mantle, crust, and atmosphere.

Data Evaluation. The noble-gas conundrums presented here have been discussed for many years in scientific circles. Only a small portion of the extant literature has been collected for this entry. Rating: 1.

Anomaly Evaluation. The nature of the conundrums varies with the noble gas being considered. Nevertheless, as a class, the anomalous abundances of these gases pose questions about the accuracy of the mainstream theories about the earth's chemical constitution (Can it be estimated from meteorite compositions?), the earth's thermal history (Were there recent catastrophic episodes?), and the chemical processes in the planet's atmosphere (How does so much helium-4 leak away?). Rating: 2.

Possible Explanations. See text below in X1-X3.

Similar and Related Phenomena. The outgassing of radon (ESC15) and methane (ESC16).

Examples

X1. Dearth of helium-4 in the earth's atmosphere. Based upon our present knowledge of the earth's constitution---both beneath our feet and in the atmosphere above---there should be 1000-3000 times more helium-4 in the atmosphere than we measure. (R2, R4)

The basic assumptions contributing to the formulation of the anomaly are : (1) All of the earth's primordial helium boiled off and escaped; (2) All currently measured helium-4 is outgassed from the earth, where it is created by the radioactive disintegration of uranium and other radioactive elements; (3) Our estimates of the quantities of radioisotopes in the earth are approximately correct; (4) The only way helium-4 can escape from the planet is via thermal ejection from the upper atmosphere; and (5) The earth is approximately 4.5 billion years old. (R2-R4)

Earth scientists are rather confident about these assumptions and freely recognize this anomaly, as in the following quotation from E.E. Ferguson et al.

"It is well known that the rate of influx of He^4 into the atmosphere from the Earth's crust greatly exceeds the present thermal loss from the atmosphere. McDonald gives the production rate as about 2×10^6 atoms/cm^2-sec. Thus one concludes that either some non-thermal process yields a greater rate of escape of helium or that the escape rate has varied in time. The time scale for such a change is dictated by the fact that the present amount of helium would be produced by radioactive decay of uranium and thorium in the Earth's crust in about two million years." (R3)

Proposed solutions. The first two proposals are quite startling; the rest do not meet such vehement objections: (1) A catastrophic event within the last two million years, say an encounter with a comet, boiled off the earth's atmospheric helium (R2); (2) The earth is only a few thousand years old, and the helium-4 has not yet reached its equilibrium level (a creationist proposal, R8); (3) Thermal escape of helium-4 is augumented by hot-ion exchange (R8) and the presence of metastable helium-4 [$He(2^3s)$] (R3); (4) The solar wind sweeps helium ions out of the upper atmosphere; and (5) Helium ions are accelerated by electrical fields in the upper atmosphere and escape as part of the "polar wind" leaking out the ends of the magnetospheric bottle. (R8) None of these proposals has been fully accepted. Perhaps the basic assumptions should be questioned. (WRC)

X2. Where does the earth's helium-3 come from? Helium-3 has been detected outgassing from the earth's crust, especially from the ocean's crust near spreading centers, but also from the continents. (R13) Unlike helium-4 (See X1 above.), helium-3 is not produced by the disintegration of any radioisotopes known to be common in the crust and mantle. Furthermore, the helium-3/helium-4 ratio for outgassing helium is some 20 times higher that for atmospheric helium. (R4)

Where could the unexpected helium-3 come from if terrestrial radioactivity is ruled out? Some possibilities are: (1) The helium-3 is mostly primordial, meaning that it was not all boiled off when the earth was formed 4.5 billion years ago (R5); (2) Very tiny amounts of helium-3 are created when lithium in the crust is bombarded by neutrons from spontaneously fissioning uranium; (3) Some of the helium-3 detected in ocean sediments is not outgassed helium but rather extraterrestrial helium-3 introduced by interplanetary dust particles (R7); and (4) Cold-fusion reactions are presently occurring within the earth! (R13) It should also be added here that extraterrestrial helium-3 can be added to the atmosphere (not the crust) by cosmic-ray neutrons reacting with atmospheric nitrogen and directly from the helium-3 component of the solar wind. (R8)

Also worth cross-referencing here is the observation that helium-3 is often associated with outgassing methane. T. Gold has employed this fact to support his assertion that much terrestrial methane is primordial rather than biogenic. See a more detailed discussion in ESC16-X3, in another Catalog volume.

Given the above facts, what is anomalous about the earth's helium-3? Earth scientists are now comfortable with the continuing outgassing of primordial helium. (R13) Therefore, the anomaly may be in the very high helium-3/helium-4 ratio for outgassing helium compared to the ratio in the atmosphere. If there is truly too much helium-3 coming from the earth---and this is not completely clear from the references consulted---the apparent imbalance with respect to helium-4 may mean that new helium-3 is being generated by some exotic nuclear reactions within the earth. This would be anomalous. (WRC)

X3. Where is the earth's missing xenon? To answer this question, we must first determine whether xenon is really missing from the earth. It is presently a fixture in geological thinking that the abundances of highly volatile elements (e.g., lead, boron, chlorine, etc.) and the atmospheric noble gases (i.e., neon, argon, and krypton) occur in the same abundances that we observe in the C-chondrites. In fact, much of what we assume about the earth's chemical constitution is determined by analogy with meteorites. That this may be a dangerous assumption is underscored by the anomaly of the "missing" xenon. Compared to the C-chondrites, atmospheric xenon is depleted with respect to neon, argon, and krypton by a factor of about 20. (R6) Unless this xenon anomaly can be explained away, the estimation of the bulk composition of the earth by analogy with meteorites will be at risk.

Possible explanations for the deficiency. (1) Primordial xenon has been preferentially trapped in terrestrial sediments and/or the Antarctic ice; (2) The earth's noble gases are non-chondritic; and (3) the earth's inventory of primordial xenon is incompletely outgassed. Actually, none of these possibilities is particularly attractive. J.F. Wacker and E. Anders favor the first, because there is a fortuitous match between the size of the xenon atom and the pore size of amorphous carbon. In other words, outgassing xenon may be preferentially trapped by amorphous carbon in the crust. (R6) M. Ozima objects to this argument because the xenon content of volcanic rocks and xenoliths is one or two orders of magnitude too low. (R9)

Ozima has also pointed out that the relative abundances of the xenon isotopes (of which there are many) in the earth's atmosphere are very different from those observed in meteorites. In addition, the xenon isotopes in a shergottite meteorite, thought to be a piece of the Martian crust, are similar in relative abundances to terrestrial abundances. The atmosphere of Mars, therefore may also have a xenon deficiency like earth's. Ozima concludes that one should be wary of using meteorites to determine planetary compositions. (R9)

References

R1. Cook, Melvin A.; "Where Is the Earth's Radiogenic Helium?" Nature, 179:213, 1957. (X1, X2)
R2. "What Happened to the Earth's Helium?" New Scientist, 24:631, 1964. (X1)
R3. Ferguson, E.E., et al; "A New Speculation on Terrestrial Helium Loss," Planetary and Space Science, 13:925, 1965. (X1)
R4. "The Ocean Yields Up Primordial Helium," New Scientist, 43:320, 1969. (X2)
R5. Clarke, W.B., et al; "Excess ^{3}He in the Sea: Evidence for Terrestrial Primordial Helium," Earth and Planetary Science Letters, 6:213, 1969. (X2)

R6. Wacker, John F., and Anders, Edward; "Where is the Earth's Missing Xenon?" Meteoritics, 19:327, 1984. (X3)
R7. Amari, Sachiko, and Ozima, Minoru; "Search for the Origin of Exotic Helium in Deep-Sea Sediments," Nature, 317:520, 1985. (X2)
R8. Vardiman, Larry; "Up, Up and Away! The Helium Escape Problem," ICR Impact Series, No. 143, 1985. (X1) (ICR = Institute for Creation Research)
R9. Ozima, Minoru; "Looking for Missing Xenon," Nature, 321:813, 1986. (X3)
R10. Staudacher, Thomas; "Upper Mantle Origin for Harding County Well Gases," Nature, 325:605, 1987. (X3)
R11. Oxburgh, E. Ronald, and O'Nions, R. Keith; "Helium Loss, Tectonics, and the Terrestrial Heat Budget," Science, 237:1583, 1987. (X2)
R12. Wakita, Hiroshi, et al; "High ^{3}He Emanation and Seismic Swarms Observed in a Nonvolcanic, Forearc Region," Journal of Geophysical Research, 92:12539, 1987. (X2)
R13. "Rocks Reveal the Signature of Fusion at the Centre of the Earth," New Scientist, p. 30, May 6, 1989. (X2)

ECD SURPRISING DISCOVERIES FROM DEEP DRILLING

Key to Phenomena

ECD0 Introduction

Just as radar targets on a screen may be misinterpreted, so surface instrumentation may produce misleading results about the inner earth. In the application of radar, it is always desirable to employ "ground truth"; that is, the comparison of actual targets with what the operator infers from his equipment. By analogy, deep holes in the crust yield "drilling truth"! Only by drilling can we verify models developed from seismograms, magnetic data, and application of physical and chemical theory. In this short chapter, it will become obvious that one should take great care in modeling inner earth from surface data alone.

In retrospect, exploring inner earth with deep drilling follows the pattern of space exploration. Scientific spacecraft produced many surprises about the earth, the moon, and the planets. Deep holes in the earth's crust will be equally productive in correcting our early models of inner earth.

ECD1 Drilling Truth Confounds Surface Science

Description. Various data from deep holes that contradict models developed from data acquired from surface instrumentation and theoretical expectations.

Data Evaluation. Very few deep holes have been drilled with science in mind.

Consequently, data here are sparse and geographically spotty. Rating: 3.

Anomaly Evaluation. The seven examples cataloged below bear testimony that the application of surface instrumentation can lead to serious misinterpretation of inner earth. Likewise, theoretical expectations in such matters as temperature and rock density may be far off the mark. The gist here is that our present models of the earth's crust are naive in some respects. By extension, this assertion doubtless holds true for the core and mantle. Rating: 1.

Possible Explanations. None required.

Similar and Related Phenomena. Space science just after the first scientific satellites and space probes were launched.

Examples

X1. Unexpected temperature profiles. In two deep holes, the temperatures have increased with depth far more rapidly than predicted.

U.S.S.R. Before drilling began on the Kola Peninsula, the scientific expectation was that temperatures would increase about 1°C per hundred meters. In practice, the rate of increase was 2.5°C below 3 kilometers. At the 10-kilometer level, the temperature was 180°C rather than the expected 100°C. (R1, R2)

Germany. At the bottom of a 3.5-kilometer hole drilled in the Oberpfalz Forest, German geophysicists measured 118°C instead of the anticipated 80°C. (R5)

A later report concerning the Oberpfalz site states that below 500 meters the temperature gradient was 28-30°C per kilometer, instead of the anticipated 22°C per kilometer. Further, at the completion of the hole at 4000 meters, the temperature was 100°C. Earlier in the drilling, at 3400 meters, the drill encountered brine with a temperature of 118°C. This is the temperature stated in the above paragraph. (R9)

X2. Unexpected density profiles. It is generally expected that rock density will increase with depth, as pressures rise.

U.S.S.R. Early results from the Kola Peninsula indicated that densities did indeed increase with depth initially, but at 14,800 feet the drill encountered a sudden decrease in density, presumably due to increased porosity. (R1)

In a later report: "Minister of Geology Yevgeny A. Kozlovsky has reported... that 'with increasing depth in the Kola hole, the expected increase in rock densities was not recorded. Neither was any increase in the speed of seismic waves nor any other changes in the physical properties of the rocks detected. Thus the traditional idea that geophysical data obtained from the surface can be directly correlated with geological materials in the deep crust must be reexamined.'" (R3)

X3. Fractured rocks with circulating fluids at great depths. Conventional wisdom has been that the high pressures deep in the earth would close rock fractures and reduce porosity to near-zero. Certainly, circulating fluids were not expected.

U.S.S.R. In Science, R.A. Kerr wrote: "The most surprising discovery in the Kola hole is 'circulating fluids' where none should be. 'Throughout the Kola superdeep borehole,' wrote Yevgeny Kozlovsky, Soviet minister of geology, in 1982, 'gases and inflows of strongly mineralized waters have been encountered, circulating through broad deformed zones. This is so even near the present base [11.5 kilometers] of the borehole...' The gases include 'methane and other hydrocarbons.' The presence of fractures open to fluid circulation at pressures of more than 3000 bars was unanticipated." (R2)

Some Western scientists have been skeptical about the presence of circulating fluids that deep. They point out that drillers often pump fluids down the drill to lubricate the bit, and that it would be hard to distinguish between these and naturally occurring fluids. (R7)

Germany. Skepticism about the deep, circulating fluids found by the drill at the Kola site diminished when the drillers at Oberpfalz also discovered hot fluids in open fractures at 3400 meters. This brine was rich in potassium and twice as salty as ocean water. Its temperature was 118°C. The German scientists were not certain as to whether the fluid was circulating; if it was, its velocity was very low. The brine also contained gases rich in carbon and helium-3. (R9) These gases, especially the helium-3, were probably primordial constituents of the earth working their way up through the mantle and crust. (WRC)

X4. Elusive discontinuities and reflectors. Seismic reflection surveys reveal many reflectors in the deep crust that presumably represent transitions from one type of rock to another. (EQD1) In addition, at about 5 kilometers, all continents are underlain by a strong velocity discontinuity called the Conrad discontinuity. At this juncture, theory has it that acidic, granite-type rocks change to basalt.

U.S.S.R. Before drilling their superdeep hole on the Kola Peninsula, Soviet seismologists discerned not only the Conrad discontinuity (at 7.5 to 8.5 kilometers) but several other reflectors as well. R. Monastersky related what they actually found via drilling. "Yet when the drill actually reached a depth of 7.5 km, the scientists did not find basaltic rock. Even at the present depth of 12 km, the drill has not crossed into the region of layered basaltic rock. The Soviets now believe that if the basaltic layers exist, they must lie much deeper." (R7)

One interpretation of these results is that the Conrad discontinuity does not represent a fundamental change in chemistry but instead metamorphic alteration brought about by heat and pressure. (R5)

Germany. Surface seismological data at the Oberpfalz Forest site indicated a rock boundary at 3 kilometers, but at the termination of drilling at 3,5 kilometers no sign of it had been found. (R5)

X5. Encounters with unanticipated rocks. Sometimes deep drilling brings up rocks that pose questions about the evolution of the continents.

North America. North American geologists have not drilled any superdeep holes like that on the Kola Peninsula, but even shallower holes all across North America have yielded surprises. Drillers have found immense quantities of so-called Laurentian granite and rhyolite in a broad band running from southern California to Labrador, mostly at depths of 1-2 kilometers, but rarely cropping out on the surface.

Rhyolite and granite have identical chemical composition, but the rhyolites form when magma erupts at the surface and cools rapidly. Granite, on the other hand, cools slowly underground. The presence of so much of these Laurentian rocks over such a wide area has remained enigmatic for years. They constitute an important anomaly, because they imply intense, unexplained thermal activity all across North America 1.3-1.6 billion years ago. (R6)

X6. Buried magnetic anomaly remains anomalous.

France. Running north-south across the Paris Basin is a strong magnetic anomaly that has puzzled scientists for over a century. Electromagnetic surveys on the surface put the magnetic body responsible for the anomaly at a depth of 3 kilometers. However, the Sancerre-Couy borehole in the Paris Basin terminated at 3.5 kilometers without finding any sign of the rock creating the anomaly. It must lie much deeper than surface instruments indicate. (R5)

X7. Surprising signs of life deep down. Although near-surface waters in caves, fractured rocks, and porous strata support bacteria and even higher forms of life, biologists did not consider life possible at depths of several kilometers.

U.S.S.R. The early Soviet reports from the Kola Peninsula were on the sensational side. They indicated that life forms and fossils had been found kilometers down. The following quotation from a 1981 article has not been elaborated upon to our knowledge.

"According to Yakovlev, however, the evidence of life at great depths had not been expected. He said accumulations of gas, fissure waters, and bromine and iodine brines all testified to some biological activity as the drill penetrated through alternating layers of igneous rocks emanating from the earth's interior and rocks of marine origin laid down during the Late Precambrian era some two billion years ago.

"Providing further details on remains of life at such depths, another geologist, B.V. Timofeyev, said microscopic fossils had been found at depths of 22,000 feet. He said that 24 species had been identified among these microfossils, representing the envelopes or coverings of single-cell marine plants known as plankton. Unlike conventional shells of limestone or silica, these coverings were found to consist of carbon and nitrogen and were said to have remained remarkably unaltered despite the huge pressures and high temperatures to which they had been subjected," (R1) The forgoing obviously raises many questions which, to our knowledge, have never been answered. For example. how can life forms survive at pressures of 3000 bars and temperatures well above 100°C? (WRC)

Sweden. The 6.8- kilometer hole drilled in the Siljan Ring in a quest for abiogenic gas and oil yielded micrometer-sized grains of magnetite. T. Gold holds that these particles were synthesized by deep-dwelling bacteria, which feed upon the abiogenic hydrocarbons rising from even greater depths. (R8) At best, this is only indirect evidence for life at depths of several kilometers.

References

R1. "Journey to the Earth's Center," San Diego Union, p. A-30, October 9, 1981. (X1, X7)
R2. Kerr, Richard A.; "Continental Drilling Heading Deeper," Science, 224: 1418, 1984. (X1, X3, X4)
R3. Cromie, William J.; "Windows to the Earth," Mosaic, 15:28, no. 6, 1984. (X2, X3)
R4. Yardley, W.D.; "Is There Water in the Deep Continental Crust?" Nature, 323:111, 1986. (X3)
R5. Kerr, Richard A.; "Deep Holes Yielding Geoscience Surprises," Science, 245:468, 1989. (X1, X4)
R6. Monastersky, Richard; "Spinning the Supercontinent Cycle," Science News, 135:344, 1989. (X5)
R7. Monastersky, Richard; "Inner Space," Science News, 136:266, 1989. (X3, X4)
R8. Kerr, Richard A.; "When a Radical Experiment Goes Bust," Science, 247: 1177, 1990. (X7)
R9. Toro, Taryn; "German Geology Hits New Depths," New Scientist, p. 24, September 29, 1990. (X1, X3)

ECG STRUCTURAL ANOMALIES INDICATED BY GRAVITATIONAL ANOMALIES

Key to Phenomena

ECG0 Introduction

Superimposed upon the earth's gravitational field are many departures from the idealized gravitational field created by a perfect, homogeneous sphere. It should be mentioned at the beginning that any deviation from any idealized reference field established by geophysicists is termed an "anomaly", even if the source of the perturbation is well-understood. In contrast, "anomalies" in this Catalog are those observations which challenge prevailing paradigms. Thus, the door is left open for the seemingly self-contradictory entity: the "anomalous gravity anomaly"!

Most of the gravity anomalies recorded in this chapter reflect deeply buried structures in the crust and mantle. The nature and origin of these unseen structures are still enigmatic. We only know that "something" more dense or less dense than its surroundings is down there. In one phenomenon (ECG4), this "something" is moving, and the gravitational field oscillates as a result. Even when geophysicists construct more sophisticated models of the earth's gravitational field, taking into account oblateness and similar factors, gravity surveys still reveal many deviations from the models.

ECG1 Remarkable Gravity Anomalies

Description. Positive and negative gravity anomalies that imply the existence of unrecognized and/or difficult-to-explain structures beneath the earth's surface.

Data Evaluation. The reports upon which this section is based are few in number and often from the semi-popular literature. The specialized literature has not yet been thoroughly researched. Rating: 3, although this rating will probably increase as work continues.

Anomaly Evaluation. The gravity anomalies cataloged here are anomalous in the sense that the subterranean structures they imply could be: (1) completely new and beyond the explanatory powers of today's earth science; (2) merely unusual in size; or (3) well-understood structures, such as faults and intrusions. In fact, we don't know what they really are in spite of all the speculation recorded below. No evaluation is possible here.

Possible Explanations. See examples below.

Similar and Related Phenomena. Deep structures implied by seismology (EQ) and magnetic anomalies (EZ); gravity data indicating large mantle inhomogeneities (ECG3).

Examples

X1. The Puerto Rico Trench gravity anomaly. This large gravity anomaly is so strong that the ocean above it is actually depressed, as described in a rather popularized account from a NASA report.

"NASA scientists have studied the Earth's waters both to insure the safety of astronauts descending on them and to increase all men's knowledge of the seas. A large group spent 10 days in the summer of 1970 examining one of the strangest anomalies below the surface. Utilizing the heavily instrumented tracking ship that is normally part of the two-way communications network linking the Manned Spacecraft Center at Houston with astronauts on Moon missions, these men electronically traced the contours of the deepest gorge in the Atlantic floor, the Puerto Rican trench. Beneath this 5-mile-deep trough lies a mysterious mass so dense that it deflects the pull of gravity, causes the ocean surface to dip a measurable amount, and throws navigators off course by falsifying the readings of their instruments." (R1)

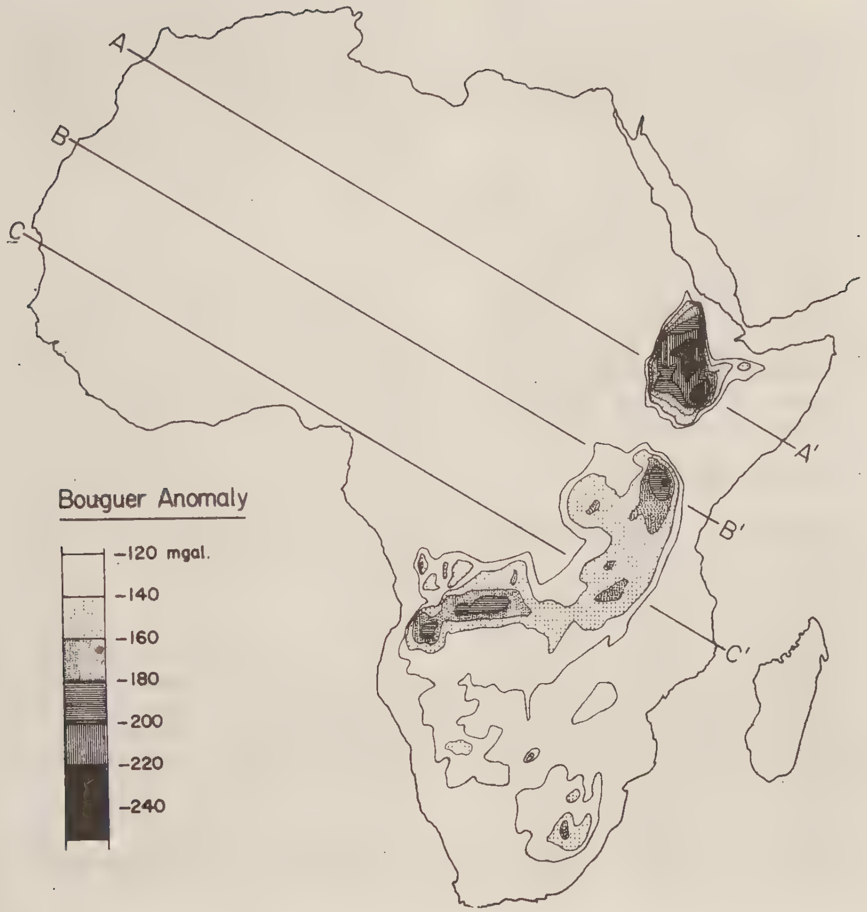
In the context of the Catalog of Anomalies, the anomaly here is that "mysterous mass". However, the surmise about a dense mass being responsible for the dip in the ocean surface seems to be in error. As explained in X6, oceanic depressions are really the consequence of gravitational lows, that is, negative gravity anomalies.

X2. The great African gravity anomaly. The discussion quoted below is based upon a Bouguer-gravity anomaly map published in 1973 by the U.S. Defense Mapping Agency.

"By far the most outstanding feature is the large negative anomaly extending from the junction of the Red Sea and the Gulf of Aden, through east Africa, and then toward west Africa at about 12°S. The anomaly is shown in Figure 1, where for clarity, all contours for values smaller than ~ -120 mgal have been omitted. This effectively filters out all the anomalies over the rest of Africa.

.....

"The anomaly is a continuous feature, although this is not clear from Figure 1 owing to the omission of contours for smaller values. On the original map, the contours from -50 to -90 mgal reveal most impressively the continuity of the anomaly, especially through east Africa. The lower value contours also show that the northwest margin of the anomaly



The great African negative gravity anomaly. (X2)

leaves the Red Sea surprisingly far north, at about latitude 17°N. The feature seems to continue for nearly 5000 km and has a width greater than 1000 km. Superimposed on this long gravity low are three more intense gravity lows (Figure 1) which are centered at 7.0°N, 39.3°E (-240 mgal), 0.5°S, 36.3°E (-200 mgal). and 11.0°S, 21.0°E (-180 mgal).

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"Comparison of Figure 1 with a geological map of Africa shows that the locations of the two largest Bouguer anomalies at 7.0°N, 39.3°E and 0.5°S, 36.3°E are remarkably well correlated with the locations of surface volcanics. It is apparent that parts of these anomalies can be attributed to the presence of very light lavas. However, the negative anomaly persists where there are no volcanics, and the large area of the anomaly with its small gradients suggests that a large part of it is due to some deep structural cause." (R2)

X3. A negative gravity anomaly stretching from the Appalachians to Nebraska. Employing new techniques for the computer proceessing gravity data, researchers at the U.S. Geological Survey found a previously unrecognized, 1000-kilometer-long strip of low gravity cutting across much of the United States. Unlike other North American gravity anomalies, such as the mid-continent gravity high, this new, low-gravity strip has no ready explanation. Interestingly enough, this strip runs through the New Madrid area of Missouri, the site of devastating quakes in 1811-1812. (R3)

This so-called "Missouri low" seems to affect surface features. For example, streams run parallel to it, caves are more abundant in it, and a swelling in the basement rock beneath the surficial sediments also parallels it.

Speculations as to the cause of the low-gravity strip include: (1) a rift that failed to open wider; (2) a suture between two pieces of colliding crust; and (3) a deep fault in the crust. (R3)

X4. A North American gravity anomaly consisting of concentric circles. J. Klasner, W. Cannon, and K. Schulz after compiling, for the first time, a gravity map of central Canada and the northern U.S., were surprised to find a pattern of gravity anomalies consisting of at least three concentric circles 2800 kilometers in outside diameter. They hypothesize that this deeply buried structure is actually the scar from the impact of a huge meteorite (the size of the state of Delaware!) made during the early history of our planet, perhaps 4 billion years ago. (R3, R4) An impact this large would be analogous to some of those seen on the surface of the moon.

X5. Indian Ocean gravity anomalies suggest "harmonic rolls". The structure described below was implied from gravity measurements from the SEASAT oceanographic satellite. Standard gravity surveys made from surface ships had not detected these "harmonic rolls".

"William Haxby of Lamont Doherty Geological Observatory in Palisades, N.Y., describes puzzling signals in the seafloor of the south Indian Ocean where relatively few ship tracks have been taken. The satellite data indicate what Haxby calls 'harmonic rolls,' regular, parallel undulations in the earth's gravity, reflected in the seafloor. The signals are as long as 1,000 kilometers, he says, and may occur at intervals of 200 km to 250 km for as many as five repetitions. They are observed in several locations, but only in the middle of the world's fastest moving crustal plates." Compression of the crustal plate seems a logical explanation, but Haxby maintains that the signals are too regular. (R5) See X6 for another feature of the Indian Ocean.

X6. A 300-foot depression in the surface of the Indian Ocean?

"There's a valley 300 feet deep in the surface of the Indian Ocean. You could sail across it and never notice it, because the dip descends and rises again gradually over its 1,200-mile width. This watery depression was discovered only after scientists noticed a slight bulge in the orbit of a satellite passing overhead, suggesting that there is a reduction in the Earth's gravity below." (R6)

This particular gravity anomaly coincides with a marked magnetic anomaly. This fact has led some scientists to explain both anomalies as the consequence of a deep valley in the earth's core (at the core-mantle boundary) that is perhaps 5-10 kilometers deep. (R7)

Both R6 and R7 specify that the Indian Ocean gravity anomaly is negative; that is, the gravitational strength is lower. The observed dip in the ocean surface is explained as due to higher-gravity areas around the depression pulling away the water over the anomaly. Note that in X1, the dip in the sea surface at the Puerto Rico Trench is blamed on a "mysterious mass".

References

R1. This Island Earth, Oran W. Nicks, ed., NASA SP-250, p. 53, 1970. (X1)
R2. Girdler, Ronald W.; "The Great Negative Bouguer Gravity Anomaly over Africa," Eos, 56:516, 1975. (X2)
R3. Kerr, Richard A.; "New Gravity Anomalies Mapped from Old Data," Science, 215:1220, 1982. (X3, X4)
R4. Simon, C.; "Deep Crust Hints Meteoritic Impact," Science News, 121:69, 1982. (X4)
R5. "Strange New Seafloor Features," Science News, 123:223, 1983. (X5)

R6. "Ocean Dip Stymies Scientists," Science Digest, 92:20, January 1984. (X6)
R7. "Satellites See Valleys in the Earth's Core," New Scientist, p. 33, May 21, 1987. (X6)

ECG2 Gravity Trends That Challenge the Continent-Accretion Model

Description. Gravity-trend data that conflict with the continental-accretion model drawn from radiometric data.

Data Evaluation. A single paper from Nature. Rating: 3.

Anomaly Evaluation. The widely accepted model of continental formation by collisional accretion is challenged in southern North America by gravity-trend data. This seems only a minor anomaly because the collision model would simply be modified by accepting the southward migration of the North American margin. Rating: 3.

Possible Explanations. See above.

Similar and Related Phenomena. Exotic terranes (ESR9).

Examples

X1. North American gravity trends. M.D. Thomas el al have prepared a gravity-trend map of North America based upon a horizontal Bouguer gravity-gradient map. With it they sketched out "a continental mosaic of gravity trend domains akin to structural domains." They maintain that contrasting gravity trends at these domain boundaries generally affirm the outward growth of North America by accretion (collisional) tectonics. In other words, North America (and presumably other continents) grew as bits of exotic crust were welded ("sutured") together by collision.

While the gravity-trend data are consistent with most accretion mosaics drawn from radiometric data, southern North America is an exception. Here, east-west orogenic belts transect a gravity-trend domain. This suggests that the collision model may not apply here. (R1)

References

R1. Thomas, M.D., et al; "Gravity Domains and Assembly of the North American Continent by Collisional Tectonics," Nature, 331:333, 1988. (X1)

ECG3 Gravity Data Indicating Large Mantle Inhomogeneities

Description. Gravimetric measurements suggesting that the earth's mantle is grossly inhomogeneous due to the accretion of large extraterrestrial bodies.

Data Evaluation. A single paper from Tectonophysics. Rating: 3.

Anomaly Evaluation. Seismic tomography also reveals many inhomogeneities in the earth's mantle, but these are usually interpreted as being chunks of subducted crust, thermal plumes, continental roots, etc. The inhomogeneities suggested by the gravimetric data cataloged here seem to imply large (10^{-3} the earth's mass) entities. These masses have different densities and compositions and are thought to be extraterrestrial bodies accreted early in the history of our planet. (R1) This "plum pudding" picture of the mantle is substantially different from the generally accepted picture of a mantle that has been stirred by thermal convection for billions of years. Rating: 2.

Possible Explanations. See above.

Similar and Related Phenomena. Mantle inhomogeneities indicated by seismic methods. (EQD1).

Examples

X1. General observations.

"A number of independent investigations have indicated the existence of large horizontal inhomogeneities of different sizes, extending to different depths, in the earth's mantle. On the gravimetric map positive and negative anomalies covering areas of several thousand kilometers are clearly distinguished. Analysis of zonal harmonics of the gravitational potential of the earth, obtained from observations of artificial satellites, have shown that the observed anomalies are considerably larger and of opposite sign than those computed for continents in hydrostatic equilibrium (isostasy). They cannot be produced by density variations in the crust, and are definitely connected with large scale horizontal inhomogeneities in the mantle. The study of tidal deformations of the earth's crust has shown that the elastic properties of the mantle in the European part of the U.S.S.R. differ considerably from those in central Asia. The seismic and magnetotelluric observations also indicate the existence of regional horizontal inhomogeneities in the mantle." (R1)

References

R1. Safronov, V.S.; "The Primary Inhomogeneities of the Earth's Mantle," Tectonophysics, 1:217, 1964. (X1)

ECG4 Anomalous Gravity Signals Following Earthquakes

Description. Faint, long-period variations in the earth's gravitational field following large, deep earthquakes.

Data Evaluation. Two paragraphs in a popular science magazine. Rating: 3.

Anomaly Evaluation. The nature of this intriguing phenomenon can only be speculated upon, as is done in X1 below. It is likely, however, that its explanation involves only some mundane oscillations of the fluid constituents of inner earth. No important scientific laws would be endangered if this is the case. Rating: 3.

Possible Explanations. Fluid motion within the earth stimulated by earthquakes.

Similar and Related Phenomena. Seismic ringing of the earth after earthquakes (GQS6); earthquake magnetic effects (GQM1); both in another volume of this series.

Examples

X1. Gravity signals following earthquakes.

"Last year, Paul Melchior and B. Ducarme of the Observatoire Royal de Belgique in Brussels published the results of their studies on changes in the local gravity field as measured by a superconducting gravimeter, which is at least 100 times more sensitive than a conventional gravity meter. Melchior and Ducarme reported that following two large, deep earthquakes in 1983 and 1984, they detected slow waves in the local gravity field that had periods of 13 to 15 hours." (R1) It was surmised that these periodical changes in intensity were due to inertial waves or oscillations of core fluids.

References

R1. Weisburd, Stefi; "The Inner Earth Is Coming Out," Science News, 131: 222, 1987. (X1)

ECH HEAT-FLOW ANOMALIES

Key to Phenomena

ECH0 Introduction

The flow of heat outward from the core and mantle to the earth's crust is, on the average, a miniscule 1.5 x 10^{-6} cal/cm^2-sec, both for the continents and oceans. Superimposed upon this general global flow are regions where the heat flow is so intense that volcanism results. Most of the earth's volcanos release their heat and lava around the edges of the tectonic plates. We have found no important anomalies to record here. All heat-flow anomalies cataloged here are associated with mid-plate volcanism, where incongruous "hot spots" occur. Earth scientists postulate that "thermal plumes" rising through the mantle create these enigmatic hot spots, but there are still questions and anomalies to be resolved in connection with the origin of the thermal plumes themselves and the distribution of the hot spots and volcanos they supposedly create.

ECH1 The Origin of Mid-Plate Volcanism

Description. The appearance of hot spots and associated volcanism in oceanic and continental plates well away from spreading and subduction zones. Hot spots seem to remain fixed geographically for geologically long periods.

Data Evaluation. The literature is extensive here. It has only been sampled so far. Rating: 1.

Anomaly Evaluation. The theory of plate tectonics does not explain how volcanism can occur in mid-plate locations. In fact, the mantle convection cells that provide the motive power for the drifting plates would seem to be inimical to any mechanism that would create long-lived hot spots under the crust. So, one might say that plate tectonics seems incompatible with mid-plate volcanism. Rating: 2.

Possible Explanations. Thermal-plume theory, which is independent of plate tectonics, claims to account for many features of hot spots and mid-plate volcanism, but it does not tell us how hot spots remain fixed in the presence of mantle convection. Another theory has water and other volatiles producing hot spots---without heat! See X2.

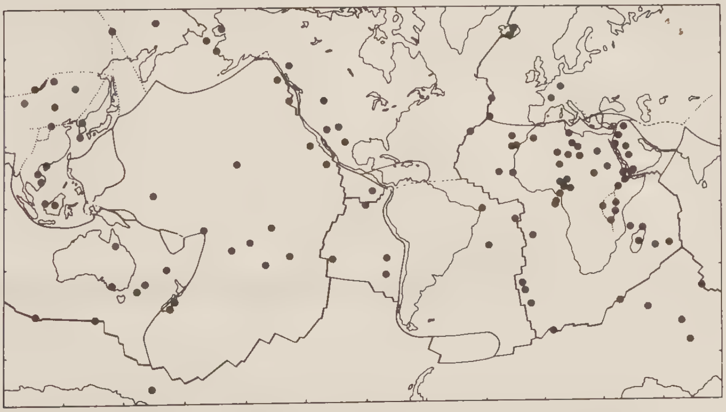
Similar and Related Phenomena. All heat-flow anomalies in this section (ECH).

Examples

X1. General observations. The phenomenon at hand was forcefully presented by W.J. Cromie in the Winter 1989 issue of Mosaic.

"One of the earth's last great riddles involves volcanoes in places where no volcanoes ought to be. Earth scientists divide the earth's outer shell into some two dozen slabs or plates, each 100 to 150 kilometers thick, that move slowly over a partly molten base, spreading apart here, colliding with each other there. The presence of volcanoes is easy to explain at both types of boundaries. But what about volcanoes that arise in the middle of plates?" (R1)

To amplify a bit, mid-plate volcanism is only one of three generally recognized types of terrestrial volcanism. The volcanos along the mid-ocean ridges and the island arcs constitute the other two varieties. These volcanos are explained as the consequences of melting processes created where the tectonic plates originate (as along the Mid-Atlantic Ridge) or are subducted (as along around the Pacific Ocean's "ring of fire"). Geologists feel that they understand these two varieties of volcanism fairly well. Mid-plate volcanos, however, are a different matter. They are not accounted for by plate tectonics. Called "hot-spot" volcanos, they seem to be the product of some phenomenon in the earth's mantle that focuses heat on small regions of the oceanic and continental plates. Quite often, especially on the oceanic plates, the hot-spot volcanos are strung out in



Map of the major recognized hot spots. Those in mid-plate locations are considered anomalous. (After K. Burke, R1, X1) long lines. (See illustration in ECH2.) Further distinguishing hot-spot volcanos from those around the edges of the plates is the composition of their lavas. For example, strontium and neodymium isotope ratios are markedly different for the lavas erupted along the Mid-Atlantic Ridge and around the periphery of the Pacific. Clearly, a different geophysical mechanism is required to explain mid-plate volcanism. (R1)

X2. A well-entrenched theory of hot spots. Hot spots found away from the edges of the tectonic plates are, according to mainstream thinking, created when plumes or blobs of hot, low-density mantle material rise and impact the crust. These buoyant plumes are somehow superimposed upon the large, thermal convection cells in the mantle that are thought to cause plate drifting. Where these plumes impact the bottom of the crust, temperatures rise and we have hot-spot volcanos. Just how and where the plumes arise is still speculative. Some earth scientists place their birthplace at the core-mantle boundary; some prefer locations higher up in the mantle. (R1, R2)

Thermal plumes handily explain such phenomena as mid-plate volcanism and the broad crustal uplifts (swells) that accompany the hot spots. They also account for the long lines of mid-plate volcanos, such as the Hawaiian chain. (See ECH2.) Very simply, the plume and hot spot stay fixed geographically while the plate moves over them. The result is a "hot-spot track", manifested as a chain of volcanos or seamounts. The explanatory appeal of plume theory is quite apparent.

As hinted at above, an important problem in plume theory is describing just how plumes deeply rooted in the mantle remain fixed for tens of millions of years while seemingly entrained in a convecting mantle. And why do plumes form in the first place? Also, there is some evidence that a few of the hot spots are not so hot after all! E. Bonatti has found that the mantle under some supposed hot spots, such as that under the Azores, is actually no hotter than normal. Rather, Bonatti says, his mineralogical studies at some hot spots suggest a different mechanism. Water and other volatiles rising through the mantle lower the melting points of the rocks, the rocks melt, and volcanism ensues---All without thermal plumes! Bonatti does not claim that all hot spots arise in this way, but he has identified a way in which volcanos can be created without thermal plumes. (R3, R4) Thus, thermal-plume theory is not totally secure. (WRC)

References

R1. Cromie, William J.; "The Roots of Midplate Volcanism," Mosaic, 20:18, Winter 1989. (X1, X2)

R2. McNutt, Marcia; "Deep Causes of Hot Spots," Nature. 346:701, 1990. (X1)

R3. Bonatti, Enrico; "Not So Hot 'Hot Spots' in the Oceanic Mantle," Science, 250:107, 1990. (X2)

R4. Monastersky, R.; "Pouring Water on the Theory of Hot Spots," Science News, 138:214, 1990. (X2)

ECH2 Anomalies of the Hawaiian Hot-Spot Tracks

Description. The double nature of the Hawaiian Chain, the apparent erratic linear motion of the purported hot spot, the different types of lava emitted, etc., for a total of six "objections" to the thermal-plume theory, as applied to the Hawaiian Chain.

Data Evaluation. The Hawaiian Chain of volcanos, including the Emperor Seamounts (which are defunct volcanos), are the most thoroughly researched of all hot-spot tracks. Only a few of the extant reports have been used here. However, the major critique of the thermal-plume theory is the work of a single geologist, and no rebuttals have yet been found. Rating: 2.

Anomaly Evaluation. The six objections to the thermal-plume theory outlined below seriously undermine the theory. Rating: 2.

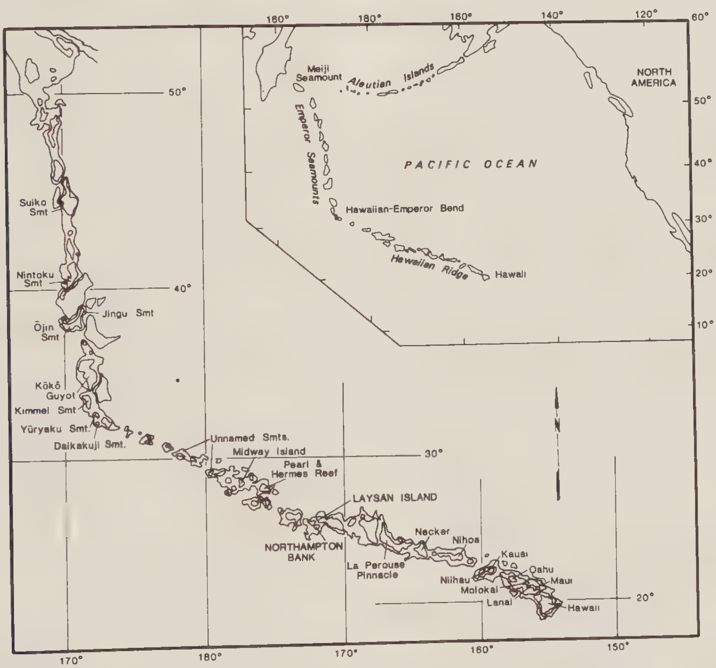
Possible Explanations. The thermal plume that built the Hawaiian Chain was wide and complex, covering a wide area and tapping different magma sources. Also, Pacific plate motion may have been erratic.

Similar and Related Phenomena. The origin of mid-plate volcanism (ECH1).

Examples

X1. General observations. The Hawaiian hot-spot track is the best studied of all examples of mid-plate volcanism. For an introduction and general description, we reply upon a quotation from W.J. Cromie.

"In some mid-plate locations, active and extinct volcanoes form chains of islands and submerged seamounts thousands of kilometers long. The Hawaiian Islands and their submerged northward extension, the Emperor Seamounts, stretch 6,000 kilometers from south of the Aleutian Islands to subtropical latitudes. A second chain runs from the Line Islands on the equator, 1,800 kilometers south of Hawaii, to the Tuamotu Archipelago at 20 degrees south latitude and ends near Pitcairn Island. A third chain, which includes the Marshall, Gilbert, and Cook



The ages of the islands and seamounts in the Hawaiian-Emperor Chain get progressively older to the north and west of the big island of Hawaii. (After G.B. Dalrymple, R3, X1)

Islands, terminates at the southeastern end of the Austral Islands.

"The Hawaiian-Emperor chain is a dramatic and well-studied example. This great scar on the earth's face is aligned roughly southeast to northwest in the direction cf motion of the plate that carries the Pacific Ocean. The ages of the seamounts and islands increase at a rate consistent with independent data on the rate of Pacific plate movement---about nine centimeters a year.

" A well-accepted explanation of this posits a deep, plumelike source of heat that is relatively fixed with reference to the shifting plate. Such a hot plume, according to the theory, forms the source of magma or molten rock that produces the volcanoes that created the island of Hawaii. Millions of years ago the island of Oahu---now 220 kilometers to the northwest of Hawaii---rested over the same spot, and the upwelling magma built the now-dormant volcanoes of that island. Tens of millions of years earlier, that same hot spot constructed islands that now have eroded to atolls and submerged seamounts.

"Along the 6,000 kilometers of the Hawaiian-Emperor chain, lavas date from the present back to about 67 million years ago. The visible islands overlie a broad uplift, 1,500 kilometers in diameter, thought to be a surface expression of a plume of hot material rising within the mantle. At the southeast end of the chain, active volcanoes, including Kilauea and Mauna Loa, continue to build the big island of Hawaii. Stretching north and west, the islands are progressively older; Nuhau Island, 500 kilometers from Hawaii, has lavas 5.5 million years old. Midway, 2,000 kilometers farther north and west, has a foundation of 28-million-year-old volcanic rock under a coral-reef cap. From here the chain continues below the surface as the Emperor Seamounts. At the 42-million-year-old Daikakuji Seamount, the track takes a sharp bend, from which the Emperors run almost due north to the 65-million-year-old Suiko Seamount.

"Geologists conclude that the hot chimney now feeding Kilauea and Mauna Loa built Suiko 65 million years ago. Then, for some 23 million years, the Pacific plate continued to drift north over that hotspot. At 42 million years ago, it changed course to a more westerly direction, creating the bend at Daikakuji Seamount. As the broad crustal uplift, marking the upwelling magma, stayed relatively fixed and the plate continued to move, the Emperor Islands sank and the Hawaiian Islands began to emerge." (R3) On the surface (and below), this application of thermal-plume theory seems most satisfactory.

To the above should be added the recent discovery of vast outpourings of lava below sealevel around the Hawaiian Islands. These flows are dated as 50,000-200,000 years old, and they have twice the area of the lava flows visible above sealevel. To account for this much greater volume of lava over a wider area than previously recognized, geophysicists added a new feature to the theory. They visualized the plume playing on the bottom of the plate like a hose, forcing it to flex up and down as it passed over the hot spot. The resultant cracking of the plate permitted much wider lava flooding, as the magma rushed through the cracks in the plate. (R2, R3)

X2. Objections to the application of the thermal-plume theory to the Hawaiian Chain. In 1966, H.T. Stearns described six features of the Hawaiian Chain that seemed at odds with the thermal-plume theory. We quote him directly.

"First, the theory would require not one but two different 'hot spots,' or chimneys, about 25 miles apart, because the Hawaiian Islands consist of paired volcanoes along two distinct parallel rifts. Or, if both chimneys tap the same hot spot, then the partition between them must be explained.

"Second, the plate would have had to slide northwestward in a decidedly jerky motion---about 25 miles fairly quickly with a stop of 500,000 or more years---long enough for distinct volcanoes to reach heights up to 13,784 feet above the ocean level, or 33,000 feet above the ocean floor....

"Third, if the 'hot spots' remained stationary and the crust moved, how is the late volcanism accounted for on Kauai, the northernmost inhabited Hawaiian island, at the same time as Kilauea and Mauna Loa have been in eruption? All of the eight main Hawaiian Islands had late Pleistocene eruptions except Lania, which has been extinct longer than any of the other islands.

"Fourth, the late Pleistocene and Holocene basalts on Kauai and Oahu contain xenoliths of rocks from deep in the mantle. Dalrymple and others state, '...geochemical and geophysical evidence indicates that nephelinitic lava is generated at greater depths than theoleiitic lava and that both come from the mantle.' If these volcanoes slid northwestward away from the 'hot spots,' how does it happen that the latest eruptions on these islands tapped a deeper source than Kilauea and Manua Loa, which are producing theolitic basalts?

"Fifth, terrigenous and pelagic sediment in cores from the deep sea floor adjacent to Kauai and to Hawaii indicate that the Hawaiian Islands were in existence in the Eocene, long after the plate was supposed to have migrated to the Emperor Chain.

"Sixth, numerous large submarine volcanoes, called seamounts, are scattered over a large area adjacent to the Hawaiian Islands. They are not in line with the main volcanoes of the Hawaiian Chain...." (R1)

References

R1. Stearns, Harold T.; "Geology," Geology of the State of Hawaii, p. 100, Palo Alto, 1985. (Cr. H. De Kalb) (X2)
R2. Monastersky, R.; "Subsea Volcanoes Found near Hawaii," Science News, 134:309, 1988. (X1)
R3. Cromie, William J.; "The Roots of Midplate Volcanism," Mosaic, 20:18, Winter 1989. (X1)

ECH3 Dearth of Continental Hot Spots

Description. The apparent near-absence of hot-spot tracks on the surface of the continental plates. Actually, continental volcanism seems to imply stationary continents and is therefore antagonistic to continental drift.

Data Evaluation. Only a single paper has been found that claims an absence of continental hot-spot tracks. Additional data and discussion are certainly desirable in such a situation. Rating: 3.

Anomaly Evaluation. If continental hot-spot tracks are truly non-existent, two serious implications arise: (1) The continents have not drifted while the oceanic plates have---an awkward situation for plate-tectonic theory; and (2) The thermal-plume theory is incorrect. Rating: 1.

Possible Explanations. If continents have deep roots, they might trap and drag thermal plumes or blobs of hot mantle with them as they drift.

Similar and Related Phenomena. The non-random distribution of hot spots (ECH4).

Examples

X1. General observations. "If continental drift as a consequence of plate motion is occurring, it should be possible to find hot-spot trails on continents if the hot spots result from deep mantle plumes as argued by Morgan. Several such trails have in fact been proposed. However, it now appears that none of them is valid, and that the distribution of several large continental volcano fields actually indicates fixed continents." (R1)

Africa. The African plate appears to have remained stationary with respect to the mantle for at least 300 million years ---a period during which the continents are believed to have drifted considerably. (R1)

Europe. The distribution of volcanic ages in central Europe is more consistent with a fixed continent than with one moving over a hot spot. (R1)

North America. Several hot-spot tracks have been proposed: New Mexico, the Yellowstone-Snake River Plain, New England/Quebec, southwestern Colorado, and from Cape Fear to Kansas. For all of these, radiometric dates show no systematic age-distance arrangements. (R1)

Australia. The Cenozoic volcanism in the eastern Australian highlands represents a better candidate as a hot-spot track. The radiometric ages of the volcanic rocks decrease fron north to south from 40 to 4 million years, as would be expected for plate motion. However, volcanic action persisted in the north, when it should have ceased according to simple hot-spot theory. Also, competing theories are able to explain this volcanism without invoking hot spots. (R1)

References

R1. Lowman, Paul D., Jr.; "Plate Tectonics with Fixed Continents: A Testable Hypothesis---I," Journal of Petroleum Geology, 8:373, 1985. (X1)

ECH4 The Non-Random Distribution of Hot Spots

Description. The concentration of hot spots in certain regions of the crust.

Data Evaluation. All we have at hand at present is a short discussion of the phenomenon in Nature. However, the source, the author's credentials, and an accompanying map of hot-spot locations are reassuring. Rating: 2.

Anomaly Evaluation. The non-random distribution of hot spots would seem to reflect on their origin. There are two schools of thought on the implications of hot-spot distribution: (1) Geoid highs occur where the upwelling mantle pushes against the crust, releasing thermal plumes in the process; and (2) The hot spots are concentrated in those regions of the crust that are more easily penetrated by the hot magma material. In other words, we have lithospheric control as opposed to geoid control. Both of these explanations are reasonable, making this phenomenon more intriguing than anomalous. Rating: 3.

Possible Explanations. See above discussion.

Similar and Related Phenomena. Dearth of continental hot-spot tracks (ECH3).

Examples

X1. Concentration of hot spots along geoid highs. Most hot spots are clustered on long-wavelength geoid highs, where the earth bulges upward on a scale of thousands of kilometers. A prominent example is the Hawaiian Superswell, Complementing this trend, the long-wavelength lows of the geoid correlate with hot-spot-free regions. (R1)

References

R1. McNutt, Marcia; "Deep Causes of Hotspots," Nature, 346:701, 1990. (X1)

ECH5 Correlation of Thermal-Plume Activity with Other Geophysical Phenomena

Description. The apparent synchronism of thermal-plume activity with such factors are paleotemperature, rate of magnetic-field reversals, and biological extinctions.

Data Evaluation. While the number of studies linking sundry geophysical phenomena to asteroid/comet impacts and terrestrial volcanism is large and impressive, very few researchers have restricted their field of inquiry to thermal-plumes and their consequent hot spots and volcanism. Additionally, the data that are available do not show strong correlations. Rating: 3.

Anomaly Evaluation. The scientific community at present strongly favors the asteroid/comet hypothesis for terrestrial catastrophism and all its associated geophysical phenomena. A small group holds out for general volcanism as the driving force behind catastrophism, but thermal-plume volcanism is only a contributor here. Considering these prejudices, the pinpointing of thermal-plume volcanism as the main cause of terrestrial catastrophism definitely goes against mainstream thinking. Even so, no sacrosanct geological or geophysical paradigms are at risk here. Rating: 2.

Possible Explanations. See X2 below.

Similar and Related Phenomena. Biological extinctions (ESB1); chemical anomalies in the stratigraphic record (ESC1); periodicity of crater ages (ETC4); correlation of magnetic reversals with other geophysical phenomena (EZP5).

Examples

X0. Background. Earth scientists continue to debate whether terrestrial catastrophism is caused: (1) by the impact of large asteroids/comets; (2) episodes of volcanism; or (3) some combination of both. A closely related question asks if terrestrial catastrophism is periodic; that is, occurring regularly every 20-30 million years. These subjects arise frequently in the Catalog of Anomalies. (See Similar and Related Phenomena above.)

In this Catalog entry, terrestrial catastrophism appears again because of its possible connection with intense thermal-plume activity, Can vigorous thermal-plume activity and its associated volcanism be linked to climatic changes, biological extinctions, and similar terrestrial phenomena? It should be pointed out here that volcanism due to thermal-plume activity must be separated from that occurring at spreading and subduction zones.

X1. Possible correlation of thermal-plume activity with other terrestrial phenomena.

A key paper on the subject appeared in 1972 (R1), long before asteroid-impact catastrophism became fashionable. In said paper, P.R. Vogt presented geological evidence supporting the idea that many of the volcanic episodes associated with thermal plumes have been synchronous and, further, that these episodes were powerful enough to have widespread geophysical and biological consequences. Vogt selected several "global parameters" and compared them with the volumes of material discharged during the various volcanic episodes along the Hawaiian Chain. After comparing the activity along the Hawaiian Chain with that on Iceland and elsewhere, he concluded that he could safely use the Hawaiian figures as representative of the magnitude of global volcanism. Vogt found the "suggestion of correlation" between high thermal-plume activity on the Hawaiian Chain and: (1) lower paleotemperatures; (2) higher rates of magnetic reversals; and (3) lower biological diversity. Vogt also remarked that thermal-plume activity seemed to peak every 50-60 million years. (R1)

X2. <u>A possible mechanism for creating periodic thermal plumes</u>. Proponents of astronomical catastrophism can account for periodicity be appealing to the regular motions of the asteroids and comets. Those earth scientists favoring volcanism as the source of periodical catastrophism have to search hard for cyclic geological phenomena. Restricting themselves to thermal-plume (or hot-spot) volcanism, D. Loper and K. McCartney postulate a mechanism transpiring in the lower mantle as a possible source of periodicity.

"The unstable layer at the base of the Earth's mantle is 100 kilometres thick and known as the D" layer. The layer transfers heat from the core to the solid mantle. According to McCartney, the layer, which is molten, thickens until it forms a plume. This plume, he says, rises through the mantle to form a hotspot volcano, leaving behind a thinner D" layer which gradually thickens until it becomes unstable in another 22 million years." (R2) Today's earth scientists prefer a 20- to 30-million-year period for terrestrial catastrophism rather than Vogt's 50 to 60 million years.

Going a step further, Loper and McCartney suggest that the D" layer supplies energy to the dynamo generating the geomagnetic field, thus modulating it with a 22-million-year signal. (R2)

<u>References</u>

R1. Vogt, P.R.; "Evidence for Global Synchronism in Mantle Plume Convection, and Possible Significance for Geology," <u>Nature</u>, 240:338, 1972. (X1)

R2, Hecht, Jeff; "Geologists Clash over Theory of Impact," <u>New Scientist</u>, p. 23, December 10, 1988. (X2)

EQ SEISMIC PROBING OF INNER EARTH

Key to Categories

EQA LOCALIZED STRUCTURES IN THE CORE AND MANTLE
EQD SEISMIC DETECTION OF LARGE-SCALE DISCONTINUITIES, ZONES, AND STRUCTURES WITHIN THE EARTH
EQQ ANOMALOUS SEISMIC SIGNALS

One of the most productive ways to plumb the secrets of "inner earth" is simply to listen to the seismic signals generated by earthquakes. The earth is a restless planet; and, if it is not restless enough, additional seismic signals can be created artificially. Thus, earth scientists have been able to accumulate an immense store of records of seismic waves as they have been refracted and reflected by the earth's internal structures. Armed with new mathematical algorithms and large computers, geophysicists have been able to discern structures on a much finer scale than previously seen in the well-known core-mantle-crust spherical sandwich.

Inner earth, its seems, harbors a panoply of intriguing velocity discontinuities, engimatic reflectors, inhomogeneities, convection cells, continental roots, and crustal slabs thrusting deeply into the mantle. Many of these structures cannot be identified at all; others are recognizable but occur where theory excludes them. Generally speaking, inner earth is at least as varied and complex as the few radial kilometers of surface geology that we can sample directly.

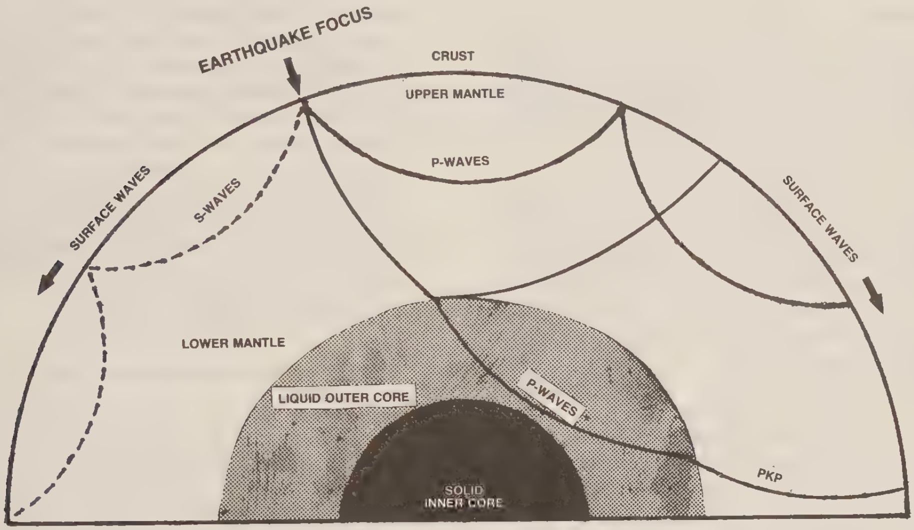
EQA LOCALIZED STRUCTURES IN THE CORE AND MANTLE

Key to Phenomena

EQA0 Introduction

Early geologists and geophysicists thought that if the confused sedimentary and upper basement rocks could be stripped away, the earth's crust and mantle would be rather homogeneous, except for occasional intrusions of magma. This expectation is partially met, because the upper crust and upper mantle are almost devoid of small-scale structures. In contrast, the lower crust (below 10-15 kilometers) and lower mantle (below 200 kilometers) teem with lateral inhomogeneities. In addition to these small structures, the continents, according to some scientists, have roots that penetrate the upper mantle and invade the lower mantle. Subducted slabs of crust also may sink hundreds of kilometers into the mantle. Finally, the core-mantle boundary seems to be a region of great complexity with topographic structures termed "continents" or "mountains". The origins of these crustal and mantle structures are for the most part mysterious. It is tempting to think of the mantle as a repository for debris sinking down from the crust or, possibly, as pathway for material expelled by the core itself. Obviously, the crust and mantle are far from static, homogeneous bodies. Their mapping and explanation present geology and geophysics with a great challenge.

A word is necessary here concerning the methods used by science in exploring the crust and mantle. Most deep structure in the earth is revealed through the analysis of naturally generated earthquake waves. Seismograph stations all over the world pool their data to assemble, via computers and various algorithms, increasingly detailed pictures of inner earth. Crustal studies, on the other hand, depend mostly upon artificially generated seismic signals. Large-scale seismic profiling projects have in recent years given scientists a view of enigmatic "reflectors" or "bright spots" in the lower crust, while the upper crust remains strangely transparent.



P and S waves radiate from earthquake focus. PP and SS waves are reflected from the surface of the earth. PcPs are reflected from the core, and PKP travel through the core. Note that S waves cannot propagate through a liquid. (X1)

EQA1 Extensive Stratification in Basement Rocks

Description. The seismic detection of widespread stratification in deep-lying basement rocks that are normally considered "hard, deformed rocks without organized structure." (R2)

Data Evaluation. The data here are limited to a short item provided by COCORP (Consortium for Continental Reflection Profiling). This organization is generally highly regarded. Rating: 2.

Anomaly Evaluation. As expressed above, the existence of great volumes of layered structure in deep basement rocks in inconsistent with prevailing views and therefore mildly anomalous. Rating: 3.

Possible Explanations. Previously unappreciated deep sedimentary strata and intrusive rocks probably account for the observations, but the volume of the unexpected strata is staggering.

Similar and Related Phenomena. More recent sedimentary rocks and layers of intrusive rocks in the upper crust which are routinely sampled directly by hammer or drill bit.

Examples

X1. Layered crust deep under middle North America. The following paragraphs were authored by the COCORP Research Group. (COCORP = Consortium for Continental Reflection Profiling.)

"Thick, laterally extensive stratified rocks lie hidden within the Precambrian basement of the central United States. The layers dwarf the overlying Phanerozoic section and may exceed in volume the entire Phanerozoic cover of the continental interior.

.....

"Although the composition and precise age of the Precambrian rocks are yet to be determined, their seismic reflection character suggests a sedimentary assemblage, at least in part. These layers occur within the Proterozoic Granite-Rhyolite province, where drilling typically recovers undeformed granite or rhyolite with ages of 1.3 to 1.5 b.y. Such prominent and orderly layering is surprising, given the widespread occurrence of granite rocks. If the layered rocks are indeed igneous, the volume of silicic volcanic material is spectacular.

.....

"The most plausible current interpretation is that extensive Proterozoic sedimentary strata, intruded by scattered granites and capped by silicic extrusives, cover this wide area." (R1)

References

R1. COCORP Research Group; "COCORP Finds Thick Proterozoic (?) Strata under Midcontinent," Eos, 69:209, 1988. (X1)

R2. Monastersky, Richard; "Boring Plains Belie Bounty Beneath," Science News, 133:363, 1988. (X1)

EQA2 Possible Deep Continental Roots

Description. Seismic detection of structures under the continents that penetrate into the lower mantle.

Data Evaluation. The debate over the interpretation of seismic anomalies found beneath the continents has continued over the last 15 years and has generated much more literature than we cite below. The question is not in the quantity and quality of the data but in their interpretation. Very simply, the data are still inconclusive. Rating: 3.

Anomaly Evaluation. The acceptance of deep continental roots would contradict the widely held view that the lower and upper mantles do not mix. Even more significant would be the difficulties deep roots would place upon the theory of plate tectonics, as developed in X1 below. Rating: 1.

Possible Explanations. The seismic structures detected far below the continents are merely cool masses of mantle material.

Similar and Related Phenomena. The possible deep penetration of subducted slabs (EQA3).

Examples

X0. Background. The question of the depth of continental roots is intimately involved with the debate over the amount of mixing occurring between the upper and lower mantle. Some geophysicists maintain that little if any material is transported across the interface between upper and lower mantles, some 200 kilometers down; others claim that the roots of the continents, as well as subducted slabs of crust (EQA3), penetrate this supposed barrier. Just which view will dominate remains undecided as of 1990.

X1. Different interpretations of the seismic data. In 1975, when many geophysicists had concluded that the continents were less than 125 kilometers thick, T. Jordan asserted that seismic data actually showed continental roots extending to depths of 400 kilometers or more. On the other hand, D. Anderson, employing the same approach as Jordan, saw no continental structure deeper than 200 kilometers. Jordan and Anderson have continued their debate to the present day, although with some convergence of views.

Jordan now maintains that continental roots are generally only 250 kilometers deep, although they may reach a maximum depth of 400 kilometers. Anderson, on the other hand, now recognizes the existence of seismic anomalies deep beneath the continents; however, he contends they are due to cold mantle rock sinking beneath the continents and are not roots per se. (R2)

Closely associated with the controversy over the depth of continental roots is the effect that such roots would have upon continental drift. Indeed, one can easily imagine the braking effect deep roots would have upon the mobility of the continents. P.D. Lowman, Jr., put it this way.

"Deep continental structure would clearly tend to inhibit if not prevent continental movement in that, as Jordan points out, at least 400 km and possibly 700 km of the mantle must translate coherently with plates. Whether this can happen, i.e., whether continental drift can occur, depends largely on the question previously discussed of the existence of decoupling zones, and on the force available to drive continent-bearing plates. At this point, it will simply be pointed out that stationary continents obviously are completely consistent with the deep structure concept." (R1) The reality of deep continental roots would thus encourage doubters of plate tectonics.

References

R1. Lowman, Paul D., Jr.; "Plate Tectonics with Fixed Continents: A Testable Hypothesis---I," Journal of Petroleum Geology, 8:373, 1985. (X1)
R2. Kerr, Richard A.; "A Generational Rift in Geophysics," Science, 248: 300, 1990. (X1)

EQA3 Possible Deep Penetration of Subducted Slabs

Description. Seismic delineation of subducted slabs of crust that appear to penetrate below 200 kilometers into the lower mantle and even beyond the 670 discontinuity.

Data Evaluation. Several observations of what appear to be slabs of crust have been found below 200 kilometers using different seismic techniques. These seismic data, however, are interpreted differently by different geophysicists. In any case, all agree that "something" is there! Rating: 1.

Anomaly Evaluation. The layered model of the earth insists that no mixing occurs between the upper and lower mantle. The presence of subducted slabs below the 200-kilometer level severely challenges the layered-mantle hypothesis. Since this hypothesis represents an important point of view in modern geophysics, deeply penetrating slabs are moderately anomalous. Rating: 2.

Possible Explanations. The same seismic data may be interpreted as merely phase changes.

Similar and Related Phenomena. Deep continental roots (EQA2); discontinuities in the earth's mantle (EQD1).

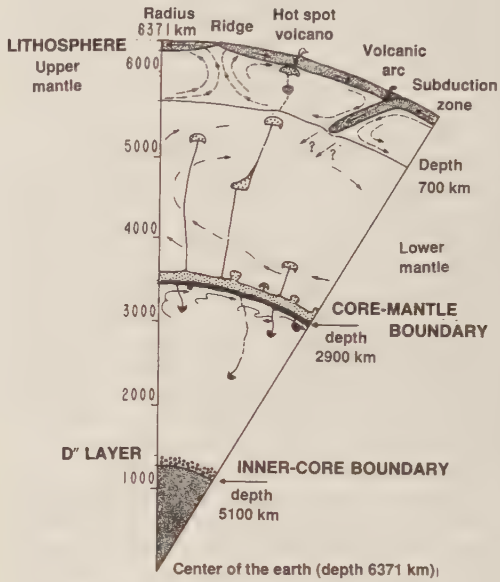
Examples

X0. Background. The debate over the reality of deeply plunging slabs of crust parallels that of the controversial deep continental roots. (EQA2) At stake is whether, as many geophysicists contend, the upper and lower portions of the mantle do not ever mix. In other words, is there a barrier, some 200 kilometers down, below which continental roots and subducted slabs cannot penetrate? As in EQA2, the main contenders are T. Jordan and D. Anderson. (R8)

The method employed by Jordan and others to demonstrate the existence of deeply penetrating slabs was sketched by T.A. Heppenheimer in the Fall/Winter 1988 issue of Mosaic.

"Such deep penetrations, as far as 1,350 kilometers, have been proposed by Jordan. He relies not on tomography for this, but on the skillful use of standard methods of seismology. His problem has been to measure the lengths of the descending slabs using data from earthquakes, with the constraint that such earthquakes occur only as far down as about 700 kilometers. But he has addressed this by studying the travel times of the resulting seismic waves. Some of them travel to a seismograph along a direction that keeps them within the slab to its lowest depths. Such waves speed up markedly, and the minimum travel time is determined from seismograms. Jordan then converts this travel-time change into a depth of penetration.

"At this point, things become particularly controversial. Indeed, the controversies involve the most basic issues of deep-earth geophysics. Jordan argues that the seismic-velocity changes that are the basis of both the tomograms and his deep-slab findings result predominantly from temperature changes at depth.



Schematic drawing of the earth's interior based on present thinking. (Adapted from V. Courtillot and J. Besse, EZP3-R15)

.....

"Caltech's Don Anderson takes a very different view. He sees changes in material properties and crystal structure, not changes in temperature, as the predominant influence at depth. Deep-mantle rock may undergo compression to form denser phases, or it may experience partial melting. Either effect, he declares, could produce relatively large changes in seismic velocities." (R5)

X1. Deep, deformed slab north of New Zealand. "Two Harvard University scientists [D. Giardini and J.H. Woodhouse] have described the ways in which the western edge of the Pacific crustal plate north of New Zealand is deformed as it plunges downward at a rapid geologic clip of seven centimeters per year. By charting the locations of 49 earthquakes deeper than 400 km, they find that as the plate approaches the 670 km boundary, it grows shorter and thicker as it fractures and telescopes in upon itself." (R1) The "boundary" or "barrier" at 670 kilometers depth is one of the major discontinuities met as one descends through the mantle toward the earth's core. See EQD1.

X2. Off northeastern Siberia. "Geophysicist Thomas H. Jordan of MIT examined the travel times of earthquake waves that passed beneath the Sea of Okhotsk, where a plate carrying the Kamchatka Peninsula is plunging under the northeastern part of Siberia. He insists that these data 'require penetration by the Kamchatka slab to depths of at least 1,000 kilometers, although penetration depths much greater cannot be excluded.' Bradford Hager, a Caltech geophysicist, takes the middle road: that the slabs meet resistance but do not go through the barrier." (R2)

X3. The central Aleutians subduction zone. That slabs of oceanic plate material actually plunge deeper into the mantle than the associated earthquake foci has been demonstrated by R. Engdahl and D. Gubbins.

"They studied how fast seismic waves traveled away from earthquakes in the central Aleutian subduction zone depending on the direction the waves took. Seismic waves speed up to 4 to 11 percent while traveling through descending slabs, which are 700°C colder and thus denser than the surrounding mantle. Engdahl and Gubbins found that waves passing downward below the slab's deepest earthquakes at 250 to 275 kilometers still sped up; the central Aleutian slab must extend below its deepest earthquakes, they inferred. 'You can't escape that conclusion,' says Engdahl, and that slab may extend as deep as 400 kilometers." (R4)

X4. A high-velocity slab under eastern North America. "Abstract. A slab-like high-velocity region 1200-1600 km beneath the east coast of North America apparently has a half-width of 450 km and a lateral extent of more than 800 km. This slab lies beneath the boundary where the Farallon Plate had been subducting for up to 120 MA. The high-velocity anomaly has been inferred previously from travel-time studies; this study uses body-waveforms to verify and refine its structure." The authors believe that this slab passed downward through the 650 km discontinuity. (R7)

X5. A deep slab beneath Peru. Abstract. "Seismograms of Peru-Brazil deep focus earthquakes recorded on the nearby Carnegie broadband station at Cuzco, Peru (CUS) are characterized by an anomalous large-amplitude P wave arrival that follows about 1.5 s after direct P. The anomalous arrival is interpreted to be an underside wide-angle reflection from the upper surface of the descending Nazca plate somewhere in the depth range 150-400 km and in a region where the slab is wholly aseismic." The authors conclude that the Nazca plate is probably continuous through 500 kilometers. (R9)

References

R1. Simon, C.; "Old Crust Grows Short. Wide as It Descends," Science News, 125:103, 1984. (X1)

R2. Cromie, William J.; "Windows to the Earth," Mosaic, 15:28, no. 6, 1984. (X2)

R3. Weisburd, Stefi.; "Plunging Plates Cause a Stir," Science News, 130: 106, 1986. (X0)

R4. Kerr, Richard A.; "Sinking Slabs Puncture Layered Mantle Model," Science, 231:548, 1986. (X3)

R5. Heppenheimer, T.A.; "The Sum of Its Parts," Mosaic, 19:38, Fall/Winter 1988. (X0)

R6. Anderson, Ian; "Seismic Waves Reveal Earth's Other Crust," New Scientist, p. 28, November 26, 1988.

R7. Vidale, John E., and Garcia-Gonzalez, Douglas; "Seismic Observation of a High-Velocity Slab 1200-1600 km in Depth," Geophysical Research Letters, 15:369, 1988. (X4)
R8. Kerr, Richard A.; "A Generational Rift in Geophysics," Science, 248: 300, 1990. (X0)
R9. James, David E., and Snoke, J. Arthur; "Seismic Evidence for Continuity of the Deep Slab beneath Central and Eastern Peru," Journal of Geophysical Research, 95:4989, 1990. (X5)

EQA4 Lateral Inhomogeneities in the Lower Mantle

Description. Lateral inhomogeneities in the earth's lower mantle, such as zones of high and low seismic velocities, determined by the analysis of earthquake waves.

Data Evaluation. In recent years, science's immense accumulation of earthquake data has been thoroughly analyzed for hints of structures in the lower mantle. The literature here is large and impressive; and we cite only a few of the many references available. Rating: 1.

Anomaly Evaluation. The existence of some lateral inhomogeneities in the lower mantle is to be expected, given its thickness and great lateral extent. These inhomogeneities turn anomalous when they seem to reflect phenomena of the earth's crust and upper mantle, such as faulting and subduction. Once again, the criterion for determining anomalousness is the dictum that the upper and lower mantles do not mix. Some of the inhomogeneities described below, particularly X4 and X5, suggest considerable traffic through the supposed barrier between the upper and lower mantles. Rating: 1.

Possible Explanations. There exists no sacrosanct barrier in the earth's mantle.

Similar and Related Phenomena. The possible existence of deep continental roots (EQA2) and deeply penetrating subducted slabs of crust (EQA3); core-mantle-boundary structures (EQA5).

Examples

X1. Recognition of lateral inhomogeneites in the lower mantle. As the science of seismology progressed and earthquake records accumulated, it became apparent that strong lateral variations (of the order of 5%) existed in the elastic properties of the rocks through which earthquake waves traveled. Even below 700 kilometers, significant lateral inhomogeneities were being detected in the early 1970s. (R1)

The paths of single seismic waves actually tell the geophysicists very little about inhomogeneities in the mantle; but, when many waves from different quakes are analyzed, irregularly shaped features can be discerned in the lower mantle. These features are zones where rock density and/or temperature vary. In the early 1980s, little more than this could be said about the nature and origin of these lower mantle structures. (R2)

Nevertheless, in these early analyses, we see the beginnings of what is now called "seismic tomography", which is the construction of three-dimensional images of mantle structures from large collections of earthquake data. More will be said about seismic tomography in X3.

X2. Elastic lenses. R. Butler has pointed out that density contrasts over large volumes of rock can give rise to focussing effects that may be confused with local structures, unless sufficient data are employed. These "lenses" can be large---as noted in the following paragraph.

"Butler noted that lenses, or anomalous regions, must have dimensions of one or more wavelengths of a P-wave, which translates to a minimum dimension in the earth of 6-8 km (for 1-s period waves). Positive correlations have been observed characteristically over large seismic arrays, suggesting the existence of lenses of several tens of square kilometers in cross section." (R3) The origin of these lenses is not discussed.

X3. Mantle lateral inhomogeneities and seismic tomography. In his 1988 review of geophysics of the earth's interior, T.A. Heppenheimer provided a capsule summary of seismic tomography.

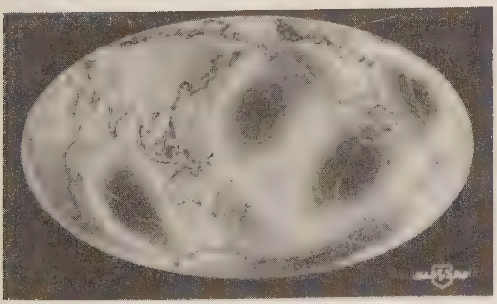
"Of the new techniques, one of the most recently evolved but most widely used is seismic tomography, invented by, among others, Adam Dziewonski and John Woodhouse of Harvard University and Robert Clayton of the California Institute of Technology. The technique's name suggests a resemblance to the technique of x-ray tomography used in medical imaging. Indeed, although the radiation source is different, the analogy is close both physically and mathematically. Consequently, in understanding the modern study of the earth's deep interior, an appropriate place to start is in a medical clinic.

.....

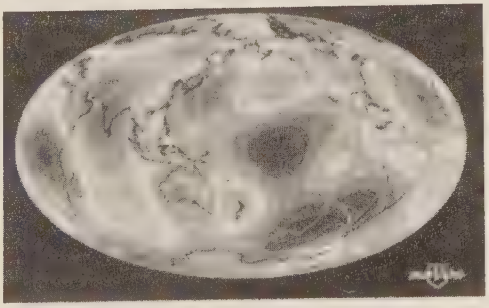
"Seismic tomography uses earthquake-generated seismic waves rather than x-rays. Between an earthquake's epicenter and a seismograph station, such waves travel along well-defined paths. Unlike the straight paths of x-rays, but like those of light rays, these paths are curved by refraction. When the distance between source and station is known, standard tables can be used to obtain the expected travel time for the seismic waves, which pass through rock at several kilometers per second. However, the actual velocities may vary.

"In the words of seismologist Tom Jordan of the Massachusetts Institute of Technology, 'The travel time might be 500 to 800 seconds. With a standard model for the propagation of waves, you can satisfy this to within a few seconds. It's that small residual that is used to make these seismic tomograms.' In medical tomography, the partial absorption of a ray of x-rays is the basis for the technique; in seismic tomography, it is the slight change of speed as the densities and elastic properties of encountered material varies along a raylike path." (R6)

DEPTH 750 KM (MODEL V3.I)



DEPTH 1500 KM (MODEL V3.I)



Tomographic maps of inner earth are based upon the velocities of seismic waves. Darker shadings indicate slower wave velocities and higher temperatures. (X3)

One appealing product of seismic tomography consists of a series of maps of seismic velocities, made at various depths, as in the accompanying illustrations. At shallow depths, directly beneath the continents, seismic tomograms indicate extensive fast regions, while regions of low velocity underly the mid-ocean ridges. Happily, this is just what one expects from the theory of plate tectonics. (R6) Therefore, though there are lateral velocity anomalies, they are not necessarily anomalous in the sense employed in the Catalog.

Of particular importance is the apparent correlation of tomogram velocity anomalies in the lowermost mantle with large static features of the earth's magnetic field calculated for the core-mantle boundary. (See EZC4.) The nature of these magneto-seismic anomalies has not been determined. (R7)

X4. Tomography below the San Andreas fault. In California, the 200 or so seismograph stations of the Southern California Array provide a detailed tomographic look at seismic velocities below the San Andreas fault. Tomograms based on some 10,000 ray paths reveal a slab-like anomaly, with 3% higher velocity, extending down 250 kilometers directly beneath the Transverse Ranges, where the San Andreas fault jogs to the left north of Los Angeles. The great depth of this slab suggests that the driving force that pushed up the Transverse Ranges came, not from tectonic plate action, as commonly assumed, but rather from the deep mantle. (R4)

It will be interesting to see if similar high velocity slabs exist beneath other mountain ranges, especially the Himalayas. If they do, a major explanatory facet of plate tectonics---mountain building---may not be required. (WRC)

X5. Tomograms of ancient subduction zones? J.H. Woodhouse, A.M. Dziewonski, and S.P. Grand have discovered, via tomography, a high-velocity seismic channel 1200 kilometers down that extends from Siberia, across Alaska, southeast across North America, and down to the Caribbean. The velocities in this strip are so high that some scientists suspect that the strip might be the remains of an ancient subduction zone. A similar strip ranges from the Red Sea, across Australia, to New Zealand. This is another possible defunct subduction zone. However, D. Anderson believes that such extreme interpretations are unnecessary because such velocity anomalies can be accounted for by chemical phase changes in shallower structures. (R5)

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R2. Simon, Cheryl; "Inner Geography," Science News, 123:280, 1983. (X1)

R3. "Elastic Lenses in the Earth," Eos, 65:65, 1984. (X2)

R4. Kerr, Richard A.; "Developing a Big Picture of Earth's Mantle," Science, 225:702, 1984. (X4)

R5. Weisburd, Stefi; "Plunging Plates Cause a Stir," Science News, 130:106, 1986. (X5)

R6. Heppenheimer, T.A.; "The Sum of Its Parts," Mosaic, 19:38, Fall/ Winter 1988. (X3)

R7. Dziewonski, Adam M., and Woodhouse, John H.; "Global Images of the Earth's Interior," Science, 236:37, 1987. (X3)

EQA5 Mysterious Structures at the Core-Mantle Boundary

Description. Structures of unknown provenance detected along the core-mantle boundary via seismic tomography and the analysis of whole-earth vibrations.

Data Evaluation. The extensive analysis of earthquake data has led to several seismic tomograms of the core-mantle boundary drawn by different groups of geophysicists. Unfortunately, these tomograms differ from one another, so the supposed structures thus delineated remain mysterious. It is even possible that these structures could be artifacts of data processing. However, the study of whole-earth vibrations---an independent technique---also indicates the presence of "something" near the core-mantle boundary. Rating: 3.

Anomaly Evaluation. The core-mantle boundary, where the hot, liquid outer core meets the colder, viscous lower mantle, is likely the scene of vigorous chemical reactions and turbulence. Some sort of texture or structure at this interface would not be at all surprising. This reasonable expectation makes these core-mantle structures more mysterious than anomalous. Rating: 3.

Possible Explanations. The core-mantle structures could be solid debris that has sunk down from above, say, pieces of subducted crust. Also, the surface of the outer core could well have structure due to internal waves and convection cells.

Similar and Related Phenomena. Lateral inhomogeneities in the lower mantle (EQA4); magnetic phenomena at the core-mantle boundary (EZC4)

Examples

X1. Seismic tomography and core-mantle topography. In 1986, O. Gudmundson et al, from the California Institute of Technology, presented their seismic tomogram of the core-mantle boundary at a meeting of the American Geophysical Union. This paper led to the well-publicized idea that "mountains" exist at the core-mantle boundary. The gist of their presentation is found in a paragraph from the December 18, 1986, New Scientist.

"The geophysicists found that the core boundary is drawn upwards to form 'mountains' under eastern Australia, the central North Atlantic, northeast Pacific, Central America and south central Asia. The boundary is pushed downwards into 'valleys' beneath the southwest Pacific, the East Indies, Europe and Mexico. These features are as high or as deep as 10 kilometers. The mountains and valleys may be the result, say the geophysicists, of long-term patterns of circulation in the viscous mantle. Cold, dense rock, they say, sinks to make depressions, while the hotter, more buoyant rock rises, drawing the core upwards with it." (R3)

The same New Scientist article related how M.A. Spieth et al, also from Caltech, proposed that the "sloshing" of the liquid core against these "mountains" might well account for the earth's irregular rotation and also erratic changes in the geomagnetic field. (R3)

Two other groups of geophysicists have also drawn tomograms of the core-mantle boundary. T. Jordan and K. Creager (MIT) have also proposed the presence of "continents" at the core-mantle boundary on the basis of their seismic tomogram of that region.

"As presented in 1986, [their tomogram] showed an extensive low-velocity region beneath the Americas and the southeast Pacific, with a similar region under Australia, the western Pacific, and the Indian Ocean. Separating them was a broad extent of high-velocity material running from north to south beneath the central

Pacific Ocean.

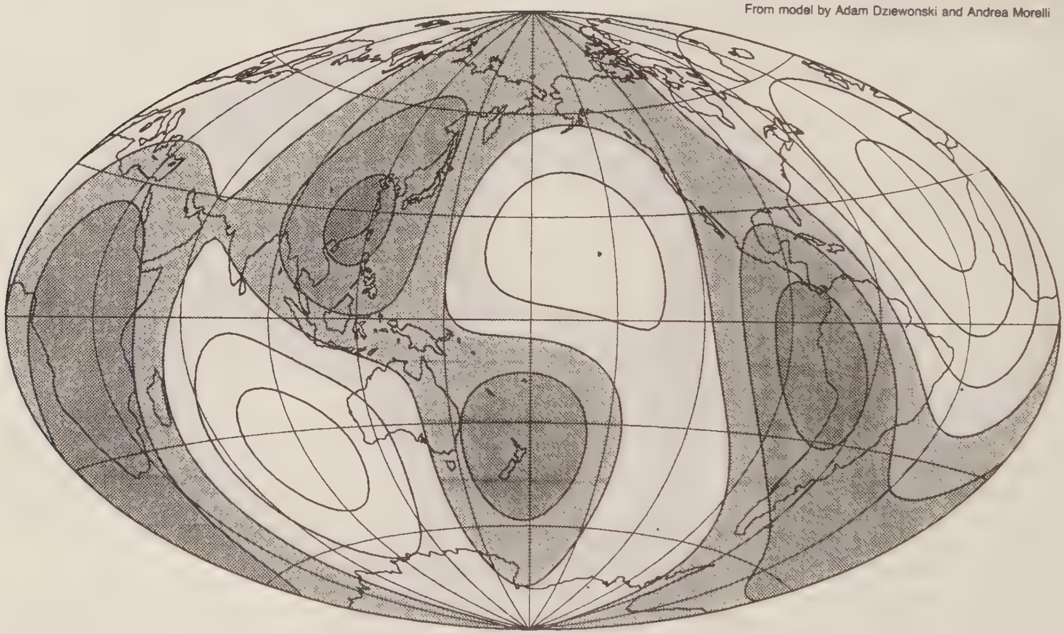
"Very quickly, this model was under challenge. Harvard's Andrea Morelli and Adam Dziewonski presented a map of the core/mantle boundary showing regions of high and low seismic velocity that were entirely different from those of Jordan amd Creager. Further, these workers had taken good care to remove the most likely sources of error. They used two independent sets of seismic-wave data, for which the inferred maps of this boundary would show opposite effects due to these errors. Since the resulting maps actually were quite similar, Morelli and Dziewonski concluded, the errors were probably small.

"The most prominent feature of this Harvard map is a ring of valleys circumscribing the Pacific Ocean. This coincides with the location of the principal subduction zones near the earth's surface, and a ring of high-velocity anomalies in the lower mantle."

.....

"Jordan and Creager, for their part, did find a potential source of error in their core/mantle boundary map. To eliminate it, along with other possible sources, they too divided their data into several independent sets, organizing these seismic measurements in ways that would cause the errors to cancel out. They too prepared several independent maps, which showed good agreement even though the maps were based on markedly different data sets. This has encouraged them to believe that they are seeing real features at this boundary. 'How well do we now agree with Morelli and Dziewonski?' says MIT's Tom Jordan. 'The answer is that we do not agree at all. It's very confounding.'"

"The latest Jordan-Creager model shows a broad ring of low-velocity material at the core/mantle interface, a band forming a wide circle with the northern Pacific in the middle. This result comes from study of virtually the same seismic velocity data as has gone into the Morelli-



A more detailed tomographic map of the core-mantle boundary as drawn by A. Dziewonski and P. Morelli. The model employed here differs from that in EQA4. Also, the darker shadings indicate increased seismic-wave velocities and lower temperatures---opposite from the maps in EQA4 (X1)

Dziewonski model. The two groups merely process their data differently, and neither can point to a feature of their algorithms that might account for the differences. Nevertheless, Jordan, no less than Dziewonski, is prepared to draw far-reaching consequences from his map.

"'Here's the great circle that this ring of high velocity corresponds to,' says Jordan, tracing it on a globe. 'Now note that this ring, at the core/mantle boundary, closely follows much of the oceanic ridge system of the Pacific, connecting the Indian Ocean Ridge with the East Pacific Rise far to the south and east. These ridges are the spreading centers, where the sea floor rifts apart. They approximate a great circle---which has the same pole of symmetry as the ring in our model. An intriguing correlation,' Jordan declares." (R6)

One's confidence is not inspired when different methods of processing the same data yield different results. One also wonders what these "mountains" and "valleys" at the core-mantle boundary really are. They could be debris sinking down from material subducted at the earth's surface, or they could be persistent irregularities produced by the core itself. (WRC)

X2, Core-mantle irregularities suggested by analysis of whole-earth vibrations. The nature of the core-mantle boundary can be investigated by seismic tomography, as in X1 above, and the by the analysis of whole-earth vibrations set in motion by earthquakes. A perfectly spherical earth would ring with a single tone like a fine bell. On the other hand, imperfections or anomalous structures in the earth would cause additional tones. The analysis of such whole-earth vibrations does not yield a detailed map of the core-mantle boundary, but it does suggest the presence of irregularities in the outer core that could very well be the "mountains" and "valleys" discerned by seismic tomography. (R2)

References

R1. Weisburd, Stefi; "Seismic Journey to the Center of the Earth," Science News, 130:10, 1986. (X1)

R2. Kerr, Richard A.; "Continents at the Core-Mantle Boundary" Science, 233:523, 1986. (X1, X2)

R3. "...and the Earth Has Mountains," New Scientist, p. 13, December 18, 1986. (X1)

R4. Gubbins, David; "Mapping the Mantle and Core," Nature, 325:392, 1987. (X1)

R5. Weisburd, Stefi; "Opening Doors to the Core, and More," Science News, 131:9, 1987. (X1)

R6. Heppenheimer, T.A.; "The Sum of Its Parts," Mosaic, 19:38, Fall/Winter 1988. (X1)

R7. Monastersky, R.; "Meeting of Mantle, Core No Longer a Bore," Science News, 134:373, 1988. (X1)

EQA6 Seismic Reflectors in the Lower Crust and Upper Mantle

Description. Seismically reflective regions or "bright spots" in the lower crust (below 10-15 kilometers) and, more rarely, the upper mantle. The apparent size of these "reflectors" is 1-10 kilometers; they are roughly horizontal.

Data Evaluation. Seismic profiling and surveys have found reflectors to be quite common in the lower crust. The specialized literature contains many papers beyond those listed below. Rating: 1.

Anomaly Evaluation. Seismic reflectors present science with at least two conundrums: (1) What is the physical nature of the reflectors? and (2) Why are they confined to the lower crust and, apparently, the upper mantle? Unfortunately, most reflectors are beyond the range of drilling. Thus, we have a common phenomenon that we cannot identify or explain in terms of its origin and distribution. Rating: 2.

Possible Explanations. Magma bodies. The presence of saline water in the crust in various guises (X1).

Similar and Related Phenomena. Deep, layered structures in the upper crust (EQA1); lateral inhomogeneities in the lower mantle (EQA4).

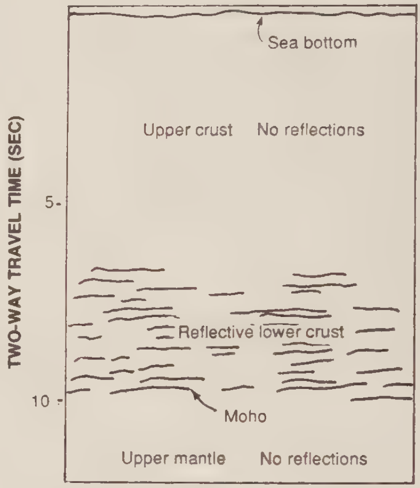
Examples

X0. Background. When the earth's deep crust is probed by artificially generated seismic waves, abnormally reflective, subhorizontal patches 1-10 kilometers long frequently appear. These are commonly termed "reflectors" or "bright spots".

X1. Anomalous concentration of reflectors in the lower crust. The crust is customarily divided into upper and lower sections, with the interface between the two sections usually set at a depth of 12-15 kilometers, or roughly half way to the Moho (Mohorovicic discontinuity), which marks the transition from crust to mantle.

D.I. Gough has summarized the differing geophysical properties of the upper and lower sections of crust:

> "The uppermost 10-15 km of the Earth's continental crust differs in several geophysical properties from the lower crust. The upper crust is electrically resistive, seismically transparent, contains nearly all intracontinental earthquake hypocentres and responds to stress elastically, with brittle fracture. The lower crust is electrically conductive, contains many seismic reflectors, is aseismic and shows ductile response to stress." (R3)



The upper crust is almost free from reflectors when compared to the lower crust. Depths in kilometers can be computed approximately by multiplying the travel times by three. (X1)

Manifestly, the two sections are radically different from one another, and the presence of reflectors in the lower crust is just one facet of a larger problem. The important question here is why reflectors are restricted to the lower crust.

Gough believes that the reflectors and other divergent properties of the upper and lower crust can be explained if the entire crust is assumed to contain saline water. He would have the water in the upper crust exist in separated cavities; in the lower crust, the water would form an interconnected film on crystal surfaces. (R3) Other scientists think that the reflectors are simply magma intrusions. This possibility has been placed in doubt by the discovery of reflectors in the crust under southeastern Georgia, which has been tectonically inactive for some 65 million years. Further, one should ask why rising magma would stop at midcrustal depths. (R5)

The problem of explaining the reflectors has been complicated by the discovery of strong, midcrustal bright spots under the Great Lakes. The crust here is over a billion years old and the stable core of the continent---hardly the place for bodies of magma. (R5)

X2. Deceptive reflections. Perhaps pertinent to the problem of lower crust reflectors is the observation that some regions in the crust producing strong laminated reflections typical of layered rocks are found, upon being probed by the drill, to be something quite different. The hole in question was drilled in Arizona in 1980 in the upper crust. A fault zone was found at the location of the layered reflections, but the composition of the rocks did not change enough to account for the strong reflections. (R1)

X3. Reflectors in the mantle. The structures that are believed to exist in the lower mantle and along the core-mantle boundary (EQA5) are typically explored employing earthquake records. In contrast, the reflectors in the crust discussed above are located by artificially created seismic waves. Recently, though, artificial seismic profiling has succeeded in reaching down into the upper mantle. Interestingly enough, abnormally reflective patches have been spotted as deep as 100 kilometers down. (R7) As with the reflectors in the crust, the nature of these upper mantle reflectors is still unknown.

References

R1. Kerr, Richard A.; "Probing the Deep Continental Crust," Science, 225:492, 1984. (X2)

R2. Oliver, Jack; "Probing the Structure of the Deep Continental Crust," Science, 216:689, 1982. (X1)

R3. Gough, D. Ian; "Seismic Reflectors, Conductivity, Water and Stress in the Continental Crust," Nature, 323:143, 1986. (X1)

R4. Barton, Penny; "Deep Reflections on the Moho," Nature, 323:392, 1986. (X1)

R5. Kerr, Richard A.; "Old and New Geology Meet in Phoenix," Science, 238:890, 1987. (X1)

R6. Klemperer, Simon, and Fifield, Richard; "Sound Waves Reflect Britain's Deep Geology," New Scientist, p. 73, February 4, 1988. (X1)

R7. "First Look at the Base of the Plates," Science News, 138:62, 1990. (X3)

EQD SEISMIC DETECTION OF LARGE-SCALE DISCONTINUITIES, ZONES, STRUCTURES WITHIN THE EARTH

Key to Phenomena

EQD0 Introduction

In EQA, our focus was on structures in the crust and mantle of limited size---smaller, say, than a few hundred kilometers. Of course, much larger entities exist within the earth. Beginning at the earth's center, we have the core, which is divided into inner and outer zones. Then, we come to the mantle, which is likewise split into two parts: the upper and lower mantles. On the outside, we find the only part of the planet we know first-hand: the crust. These concentric layers that form the earth are pictured in all of the textbooks, and their general arrangement and dimensions form the baseline model by which we identify anomalies.

The large-scale anomalies of inner earth take several forms: (1) the several velocity discontinuities in the mantle; (2) the poorly understood convection cells, also in the mantle; (3) zones and channels in the mantle where seismic velocities are anomalous; and (4) the unexpected figure of the inner core. We might also have included the core-mantle boundary in this chapter, but because this interface seems to be adorned with small-scale structure, it was assigned to EQA5.

The interfaces and structures of this chapter are known primarily through the way in which they reflect, refract, and otherwise affect seismic waves. With the help of large computers and an immense fund of earthquake data, we are finally beginning to make out what entities constitute inner earth. Geophysicists resemble doctors examining a patient for internal complaints. The main difference being that opportunities for biopsy and dissection are much more limited.

EQD1 Velocity Discontinuities in the Upper Mantle

Description. The detection, through the study of earthquake records, of well-defined discontinuities in the upper mantle, where seismic velocities change sharply.

Data Evaluation. Many years of accumulated earthquake records attest to the existence of strong velocity discontinuities between the crust and upper mantle (the Moho) and the upper and lower mantles (the 670-kilometer discontinuity). Evidence is also very convincing for lesser velocity discontinuities at 400 and 520 kilometers. Rating: 1.

Anomaly Evaluation. Velocity discontinuities are considered anomalous only when they cannot be reasonably accounted for by prevailing hypotheses. While the 400- and 520-kilometer discontinuities (X3) can be readily explained in terms of phase changes, the Moho (X1) and the 670-kilometer discontinuity (X2) cannot. The Moho is too variable in depth, configuration, and time to be written off as a simple phase change. Likewise, the 670-kilometer discontinuity is too profound to be a mere phase change, for it seems to offer physical resistance to slab penetration and separates upper- and lower-mantle convection patterns. These two important features of inner earth are far from being explained to everyone's satisfaction. Rating: 1.

Possible Explanations. Changes in the physical properties of the mantle due to phase changes or chemical differentiation. Structural changes created by, for example, sills and trapped slabs.

Similar and Related Phenomena. Zones in the mantle where seismic velocities are abnormally high, low, or anisotropic.

Examples

X1. The Moho's anomalies. The Moho (Mohorovicic discontinuity) marks the boundary between the earth's crust and mantle. For seismic waves, it is where their velocity suddenly increases to over 8 kilometers/second. Rock densities also increase here from crustal values of 2.2-2.7 to about 3.3 at the top of the mantle. Since A. Mohorovicic discovered it in 1909, the Moho has been considered a fairly well-behaved feature of the crust. Beneath the ocean floors it is a nearly constant 6-7 kilometers deep; while under the continents it is an average 35 kilometers down, a bit more under mountain ranges. Such is the "classical" Moho. Recent seismic profiling, however, portrays the Moho as a rather fickle entity.

(1) Although usually thought of as a sharp mirror-like boundary, the Moho in some places is fuzzy and seems to be a zone of mixed crustal and mantle rocks a few kilometers thick. (R9) It is particularly diffuse under Kansas, Wyoming, Minnesota, and the Colorado Plateau. (R6)

(2) On some seismic profiles several reflecting layers appear, only one of which corresponds to the classical Moho. (The classical Moho was determined by rafracted seismic waves, not the reflected waves employed in seismic profiling.)

(3) Double Mohos exist. (R5)

(4) Relict Mohos are sometimes left behind by major tectonic events. (R5) In fact, in volcanic regions, the Moho may be changing all the time. (R9)

(5) The oceanic reflection Moho is established only 100 million years after the creation of new oceanic crust. (R5)

(6) The Moho is remarkably flat beneath the Cordilleran mountain belt that stretches from Alaska to Guatemala, despite the deep faulting and the suturing of terranes evident at the surface. (R6)

(7) In the Himalayas, a younger mountain belt, the Moho is discontinuous, jumping from one level to another. (R6)

Earth scientists did not know exactly what the classical "refraction" Moho was, and the new "reflection" Moho is even more mysterious. (Of course, the classical Moho is still there!) Two schools of thought hypothesize about the Moho. The structurists prefer patterns of alternating lamellae, such as sills; the propertyists try to explain the discontinuity in terms of changes in materials, such as free water in the lower mantle. (R5) We will probably never find out what the Moho really is until we drill through it.

X2. The unknown nature of the 670-kilometer discontinuity. The official boundary between the upper and lower mantles occurs at 670 kilometers (the figure of 650 kilometers is often used). The speed of seismic waves increases suddenly at this depth, as it did for the Moho far above. But the change at 670 kilometers is more profound. First, earthquakes essentially cease at this level. Whatever forces cause deep-focus quakes cease operating here. (See EQQ1 for more on deep-focus earthquakes.) (R1) Second, the seismic evidence for deeply penetrating slabs of crust also suggests that these descending slabs encounter physical resistance at about 670 kilometers. This resistance is so great that the slabs seem to deform and perhaps fracture. (R1, R2) As discussed in EQA3, debate continues as to whether slabs actually penetrate below this discontinuity into the lower mantle proper. In this connection, it should be noted that tomograms computed for depths just above and just below the 670-kilometer discontinuity show substantial similarities. The implication is that "something" does indeed extend across the discontinuity. A.M. Dziewonski and J.H. Woodhouse conclude:

> "What is certain, however, is that the level of heterogeneities in the vicinity of the 670-km discontinuity is elevated in comparison with those at 500 and 800 km, thus indicating the existence of dynamically important processes at this boundary." (R7)

Note the use of the word "dynamically".

Velocity changes at mantle discontinuities are usually explained by phase changes induced by increasing pressures. At the 670-kilometer level, a possible phase change is an isochemical switch from spinel (Mg_2SiO_4) above to perovskite ($MgSiO_3$) + magnesiowuestite (Mg, Fe)O. (R10) But because this velocity discontinuity is so sharp, some earth scientists argue for a more profound change that involves a change in actual composition. One suggestion is a transition from olivine + spinel to a silica-rich lower mantle of perovskite. (R4, R10)

Further, one must also account for the apparent physical resistance to slab penetration of the discontinuity. A.E. Ringwood and T. Irifune have advanced a model of the mantle in which young, thin, relatively buoyant, subducted oceanic plates are gravitationally trapped in a stable layer between 600-700 kilometers. This barrier would isolate separate convection patterns in the upper and lower mantles, as well as acount for the seismic velocity change. However, mature, thick, dense slabs could still break through this physio-chemical barrier---perhaps undergoing damage in the transit---and become entrained in the circulation of the lower mantle. (R10)

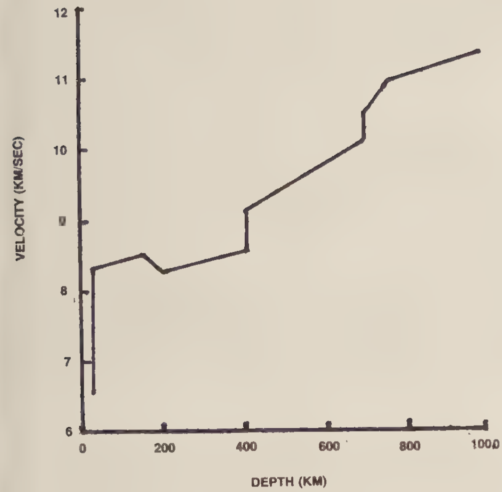
X3. Other velocity discontinuities in the upper mantle. Studies of seismic data reveal several other velocity discontinuities, but only three of these have garnered enough scientific support to recognize here.

220-kilometers. Numerous studies hint at a velocity discontinuity at this depth, but a recent study of stacked images of long-period seismic data by P.M. Shearer sees little evidence for a sharp, global discontinuity at 220 kilometers. If such a discontinuity is ever recognized, it could be ascribed to either a change between garnet lherzolite and eclogite or a region of aligned olivine crystals. (R12)

400-kilometers. The sharp velocity change at this depth is probably the consequence of a pressure-induced phase change between the alpha and beta phases of olivine. (R4, R12) This discontinuity is widely accepted as real.

520-kilometers. At this depth, the velocity change probably signals a phase change from beta olivine to spinel. (R11, R12)

Are these discontinuities anomalous? The answer is this question is probably "no", because geochemists can point in each case to reasonable, pressure-induced phase changes.



This plot of compressional P-wave velocities with depth reveals three strong velocity discontinuities. (X3)

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R2. Cromie, William J.; "Windows to the Earth," Mosaic, 15:28, no. 6, 1984. (X2)
R3. Kerr, Richard A.; "Sinking Slabs Puncture Layered Slab Model," Science, 231:548, 1986. (X2)
R4. Weisburd, Stefi; "Plunging Plates Cause a Stir," Science News, 130: 106, 1986. (X2)
R5. Barton, Penny; "Deep Reflections on the Moho," Nature, 323:392, 1986. (X1)
R6. Weisburd, S.; "The Moho Is Immutable No More," Science News, 130: 326, 1986. (X1)
R7. Dziewonski, Adam M., and Woodhouse, John H.; "Global Images of the Earth's Interior," Science, 236:37, 1987. (X2)
R8. Heppenheimer, T.A.; "The Sum of Its Parts," Mosaic, 19:38, Fall/Winter 1988. (X2)
R9. Klemperer, Simon, and Fifield, Richard; "Sound Waves Reflect Britain's Deep Geology," New Scientist, p. 73, February 4, 1988. (X1)
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R11. Wood, Bernard, and Helffrich, George; "Internal Structure of the Earth," Nature, 344:106, 1990. (X2, X3)
R12. Shearer, Peter M.; "Seismic Imaging of Upper-Mantle Structure with New Evidence for a 520-km Discontinuity," Nature, 344:121, 1990. (X2, X3)
R13. Olson, Peter, et al; "The Large-Scale Structure of Convection in the Earth's Mantle," Nature, 344:209, 1990. (X2, X3)

EQD2 Channels and Zones

Description. Layers in the mantle where seismic velocities depart from the generally smooth curve showing velocity increasing with depth (and pressure). In contrast to the discontinuities where seismic velocities change abruptly in response to phase changes and/or chemical differentiation, the velocity changes in channels and zones are less precipitous. They are thought to signal temperature changes in the mantle.

Data Evaluation. Little has been uncovered about these channels and zones. The references listed mention them only in passing. Rating: 3.

Anomaly Evaluation. Channels and zones are immediately anomalous because we do not know what they are physically. If they do represent temperature variations in the mantle, as is thought to be the case with the LVZ (Low Velocity Zone), the changes sometimes conflict with what one would expect from the hypothesis of plate tectonics. Rating: 2.

Possible Explanation. None offered.

Similar and Related Phenomena. Tomographic "images" of mantle convection cells, which are discerned from temperature-induced velocity changes (EQD4).

Examples

X1. Absence of the Low-Velocity Zone (LVZ) under the continents. The LVZ normally occupies that region of the upper mantle between 50 and 150 kilometers down. Although called a "low-velocity" zone, the LVZ is really a zone where seismic velocities do not increase as rapidly with depth as they should, according to theory. Because of this characteristic, the LVZ is commonly thought to be a zone where partial melting of the mantle occurs. This interpretation of the LVZ is welcome to proponents of continental drift, because the LVZ would constitude a global, rather plastic layer upon which the tectonic plates could move.

Not only is the real nature of the LVZ unknown, but it is definitely not a global phenomenon. In fact, the LVZ seems to be absent under the continents ---just where it is most needed to lubricate continental drift. Instead, the LVZ is found under the ocean basins and those continental areas that have been tectonically active recently. (R3, R7)

In sum, the LVZ is anomalous for want of knowledge about its nature and for its reduction of support for continental drift. (WRC)

X2. The mysterious D" layer. Just above the core-mantle boundary resides the so-called D" layer. Like the LVZ, it is a region where seismic velocities do not increase as required by theoretical estimates of mantle pressure. (R4, R7)

X3. Geographically limited zones in the mantle where seismic velocities are abnormal.

Northwestern Pacific. From an examination of earthquake travel times, D.A. Walker and W. Mansfield believe that there is an "extreme anomaly" in the northwestern Pacific between 21° and 33°, where upper-mantle seismic velocities are abnormally low. (R2)

French Polynesia. "The region of sea floor beneath French Polynesia (the "Superswell") is anomalous in that its depth is too shallow, flexural strength too weak, seismic velocity too slow, and geoid anomaly too negative for its lithospheric age as determined from magnetic isochrons." These characteristics are thought to be due to excess heat and extremely low viscosity of the upper mantle in this part of the world due, perhaps, to a mantle reservoir enriched in heat-generating radioisotopes. (R6)

Central Mid-Atlantic Ridge. According to plate tectonics, the ocean ridges are underlain by hot zones in the mantle, in which seismic velocities would be abnormally low. Actually, under the central Mid-Atlantic Ridge, seismic velocities are fast and, therefore, the mantle cool, contrary to expectations. (R1)

X4. Seismic-velocity anisotropy. "Shock waves produced by earthquakes travel faster through the Earth when going in a north-south direction than when they travel east-west.

"When these waves, called seismic waves, travel east-west they take two seconds longer to reach a point on the other side than if they travel north-south. The measurements of velocity takes the slightly wider girth of the Earth from east to west into account.

"According to Donald Anderson, director of the seismological laboratory at the California Institute of Technology (Caltech): 'All of the possible explanations of this phenomenon are outrageous.'" (R5)

References

R1. Kerr, Richard A.; "Developing a Big Picture of Earth's Mantle," Science, 225:702, 1984. (X3)
R2. Walker, Daniel A., and Mansfield, William; "Travel-Time Anomalies of the Northwestern Pacific Upper Mantle," American Geophysical Union, Transactions, 46:541, 1965. (X3)
R3. Lowman, Paul D., Jr.; "Plate Tectonics with Fixed Continents: A Testable Hypothesis---I," Journal of Petroleum Geology, 8:373, 1985. (X1)
R4. Heppenheimer, T.A.; "The Sum of Its Parts," Mosaic, 19:38, Fall/Winter 1988. (X2)
R5. "Earthquake Waves Give 'Outrageous' Result," New Scientist, p. 38, February 18, 1988. (X4)
R6. McNutt, Marcia K., and Judge, Anne V.; "The Superswell and Mantle Dynamics beneath the South Pacific," Science, 248:969, 1990. (X3)
R7. Olson, Peter, et al; "The Large-Scale Structure of Convection in the Earth's Mantle," Nature, 344:209, 1990. (X1, X2)

EQD3 Possible Structural Anomalies of the Inner Core

Description. Hints from the analysis of earthquake waves that the inner core may depart from its theoretically expected shape: an oblate spheroid.

Data Evaluation. Literature on the nature of the inner core is skimpy although growing. Travel-time and modal analysis are complicated and controversial. Rating: 3.

Anomaly Evaluation. If the inner core departs from the oblate spheroid expected from dynamics, we have a significant anomaly. Verification of a prolate geometry would be startling in view of the fact that the outer figure of the earth is that of an oblate spheroid. Rating: 1.

Possible Explanation. None offered.

Similar and Related Phenomena. The possible prolate figure of Mercury (AHE2).

Examples

X1. Apparent prolate shape of the inner core. The earth's inner core, which is thought to be solid, has been slow to yield its secrets to earthquake-wave analysts. Modal and travel-time studies are extremely complex---and controversial as well. The claim that the inner core is actually prolate in shape is by no means universally accepted.

Some geophysicists calculate that the prolate core has a polar radius that is 100 kilometers longer than its equatorial radius, with the axis of symmetry parallel to the earth's axis of rotation. (R1, R2) This prolate shape is anomalous from the dynamic standpoint, because one would expect the inner core would be oblate like the earth-as-a-whole.

X2. Other suggested features of the inner core. Even less certain than the claims of a prolate core are those for inner-core heterogeneity and, even more remarkably, hexagonal symmetry! (R2)

References

R1. Gubbins, David; "Mapping the Man-

tle and Core," Nature, 325:392, 1987. (X1)
R2. Dziewonski, Adam M, and Woodhouse, John H.; "Global Images of the Earth's Interior," Science, 236:37, 1987. (X1, X2)

EQD4 Anomalies Associated with Mantle Convection Cells

Description. Tomographic and surface geological evidence that the convection-cell pattern of the earth departs from that predicted by plate tectonics and the two-layer-mantle model. There are actually two different kinds of anomalies cataloged here, but they are closely related.

Data Evaluation. The data below come from two sources: (1) seismic tomography, which is not fully accepted by many earth scientists; and (2) the apparent absence of surface indications of mantle convection cells. Both classes of data are considered weak. Rating: 3.

Anomaly Evaluation. In X1, below, the two-layer model of the mantle is at risk because seismic tomography provides some evidence of whole-mantle convection. In X2, the role of mantle convection in powering continental drift is questioned due to the lack of surface evidence. Since the model of mantle convection plus its dovetailing with plate tectonics represent a key concept in modern geology, the anomalies here are important---even though the data supporting them are weak. Rating: 1.

Possible Explanations. The mantle incorporates a still-mysterious "transition zone" that offers some resistance to convective flow but does not prevent it completely.

Similar and Related Phenomena. Deeply penetrating slabs that seem to invade the lower mantle. (EQA3)

Examples

X0. Background. The reigning hypothesis of plate tectonics requires a motive force to transport plates horizontally across the globe. This force is usually taken to be that provided by thermal convection cells in the mantle. Relict and radiogenic heat from the core is carried to the earth's surface by upwelling, hot, plastic mantle material rising along spreading centers, such as the Mid-Atlantic Ridge. Spreading out horizontally, the mantle material cools and then sinks at the subduction zones. Those features of mantle convection cells that are at odds with this model must be considered anomalous.

P. Olson et al, in a recent number of Nature, employ three-dimensional seismology (seismic tomography) to sketch out the mantle's convection cell structure. In their Abstract they conclude: "Seismic tomographic images reveal a large-scale pattern of convection in the upper mantle compatible with surface plate motions, demonstrating the central role of mantle convection in plate tectonics. A circum-

Pacific ring of descending flow extends throughout the lower mantle. The most controversial issue is the amount of mass exchanged between the upper and lower mantle." (R4)

Thus, in its broadest aspects the hypothesis of plate tectonics is supported by seismic tomography of the mantle.

X1. Descending convection currents are continuous throughout the whole mantle. A major unresolved question about the earth's mantle is whether it is separated into two separately-convecting zones by the 670-kilometer discontinuity. As in EQA2 and EQA3, our baseline for establishing anomalousness is the widely held opinion that the mantle is so divided. (R1, R3)

The still-controversial technique of seismic tomography provides us with crude images of the mantle's convection pattern. P. Olson et al report their recent conclusions below.

"The images from global seismic tomography...may be interpreted in terms of cold downwelling and warm upwelling regions, confirming that large-scale subsolidus convection is ubiquitous in the mantle. Comparison of convection patterns in the upper and lower mantle indicate that convection is not composed of a simple pattern that can be traced continuously from the surface to the CMB [Core-Mantle Boundary]. Instead, it seems that the major descending currents may be continuous, but the major upwellings are not." (R4)

The seeming continuity of descending currents contradicts the two-zone mantle hypothesis. However, the discontinuity of the upwellings tells us that there really is "something" mysterious happening at the 670-kilometer discontinuity. Our knowledge of the mantle is itself "discontinuous" here. (WRC)

X2. Lack of convection-cell surface signatures. J. Maddox, editor of Nature, put this concern into words.

"If the present disposition of the continents and of the plates on which they are mounted is simply to be explained by a pattern of convection cells, at least some features of that pattern must have persisted for some 180 million years, the age of the oldest rocks so far found in the oceanic crust (in the south-east Pacific). So one would expect that the outlines of these convection cells would by now have been fully described, and the outlines of their ascending and descending walls drawn out on maps as befits important influences on the surface structure of the Earth." (R2)

The vague discontent expressed by Maddox hardly constitutes an anomaly, particularly since subsurface seismic tomography does seem to confirm the basic features of plate tectonics. (WRC)

References

R1. Simon, Cheryl; "Inner Geography," Science News, 123:280, 1983. (X1)
R2. Maddox, John; "What Happens in the Mantle?" Nature, 307:591, 1984. (X2)
R3. Kerr, Richard A.; "Developing a Big Picture of the Earth's Mantle," Science, 225:702, 1984. (X1)
R4. Olson, Peter, et al; "The Large-Scale Structure of Convection in the Earth's Mantle," Nature, 344:209, 1990. (X0-X2)

EQQ ANOMALOUS SEISMIC SIGNALS

Key to Phenomena

EQQ0 Introduction

This category, presently occupied by only one entry, is designed to accumulate those naturally generated seismic signals that cannot be ascribed to ordinary earthquakes.

EQQ1 Deep-Focus Earthquakes

Description. Seismic signals indicating earthquake-like events more than 70 kilometers deep.

Data Evaluation. Thousands of deep-focus earthquakes have been recorded in recent years. Only a few recent references have been used here. Rating: 1.

Anomaly Evaluation. Theoretically earthquakes cannot occur below about 70 kilometers, because there the temperatures and pressures are such that rocks flow rather than break. The mechanism for ordinary quakes therefore does not exist below 70 kilometers. Other mechanisms have been proposed, but none is close to being fully accepted. Still, the probability is that a suitable mechanism will be found without bending the laws of physics and chemistry. Even so, deep-focus earthquakes represent a major geophysical puzzle. Rating: 2.

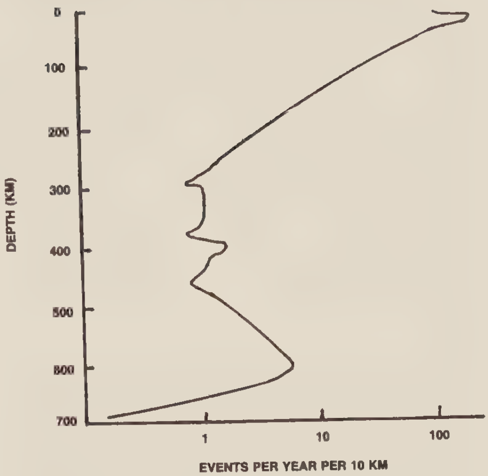
Possible Explanations. Sudden phase changes on minerals. See X2 below.

Examples

X1. General observations. The materials of the earth's mantle become ductile below about 70 kilometers; that is, they flow under stress rather than crack catastrophically. Since ordinary earthquakes depend upon such catastrophic rock failure, it would seem that temperatures and pressures in the mantle would preclude earthquakes below roughly 70 kilometers.

This expectation is not met in the real world. Since 1964, more than 60,000 quakes have been recorded below 70 kilometers---some as far down as 700 kilometers. In fact, as the figure indicates, earthquake frequency actually increases between 450 and 600 kilometers. Below 700 kilometers, however, no quakes at all are recorded. Interestingly enough, the cutoff occurs close to the 670-kilometer discontinuity marking the boundary between upper and lower mantles.

Deep-focus earthquakes are not randomly distributed. Almost all of them occur near subduction zones along inclined zones that begin at the surface and extend downward to the 700-kilometer cutoff. This slanting zone is now termed the Wadati-Benioff zone. In the plate tectonics hypothesis, this is just where cool slabs of crust dive into the hotter mantle. But not all deep-focus quakes rumble from subduction zones. Some big ones have shaken Romania and the Hindu Kush, where no subduction zones are presently active. One final point: deep-focus earthquakes are almost never followed by the aftershocks so common after shallow events. In several ways, then, deep-focus earthquakes are fundamentally different from their shallow cousins. (R1)



The frequency of earthquakes drops off with increasing depth but then increases again at about 600 kilometers. (Adapted from Scientific American, 260:48, January 1989, X1)

The deep-focus earthquakes that take place well away from known subducting slabs may, in fact, tell us something about what happens physically to deeply penentrating slabs. The Abstract of a 1990 paper G. Ekstrom elaborates.

"Benioff zones are generally recognized as the trajectories of oceanic lithosphere subducted into the Earth's mantle. The deeper portions of these zones often appear as thin, smoothly bending, coherent slabs. Occasionally, deep earthquakes occur outside of these slabs at horizontal distances of one to several hundred km. If deep earthquakes are confined to occur within recently subducted lithosphere, such anomalous events suggest that the slab thickens, doubles up, or flattens at the base of the upper mantle." Preliminary analysis of quakes outside of slabs indicate that these earthquakes have different focal mechanisms than the quakes occurring inside the slabs proper. (R4) The clear implication is that slab- and extraslab-earthquakes, though both of the deep-focus class, have different origins.

So far, the discussion has dwelt on the locations of deep-focus quakes. It is necessary to address the question of how they can take place anywhere at such great depths.

X2. Attempts at explaining deep-focus earthquakes. It is tempting to say that the deep-focus quakes occur within the cool, subducted slabs of crust. This cannot be because, even if the temperature in the slab is hundreds of degrees cooler than the surrounding mantle, brittle fracture cannot occur in the slabs under the conditions prevailing 700 kilometers deep. (R1)

A second approach to explaining the deep-focus quakes appeals to the water of hydration present in some minerals. At certain combinations of temperature and pressure, it is argued, water of hydration is released and lubricates the rock surfaces in subducted slabs. The result is a deep-focus earthquake. We do know that the injection of fluids into surface wells can stimulate small, shallow earthquakes. Deeper down, we would expect the water of hydration to be released at rather sharply defined depths, where the pressures and temperatures are favorable. Unfortunately for this suggestion, deep-focus quakes do not show this sort of vertical distribution. (R1)

Mineral phase changes have also been proposed as quake-generating mechanisms. If a mineral changes to a denser phase very suddenly, conditions for an implosion might exist. Again unfortunately, the characteristics of deep-focus quakes are not those of implosion events. (R1)

Recently, H.W. Green and P.C. Bumley have reported on some laboratory experiments that may be pertinent.

"From low-pressure experiments on the olivine-analogue germanate Mg_2GeO_4, they find that the phase transition depends critically on the shear stress as well as on the hydrostatic stress. Although stress is relieved by ductile flow at both low and high temperatures, they find a narrow temperature range where there is unstable, catastrophic failure as tiny lenses of spinel form and link up as 'anticracks' along the plane of maximum shear stress." (R2) Herein, perhaps, there is a mechanism for causing deep-focus earthquakes.

References

R1. Frohlich, Cliff; "Deep Earthquakes," Scientific American, 260:48, January 1989. (X1, X2)
R2. Frohlich, Cliff; "New Rumbles from Deep Sources," Nature, 341:687, 1989. (X1, X2)
R3. "'Anticracks' in Mantle Creat Deep Earthquakes," New Scientist, p. 33, November 4, 1989. (X2)
R4. Ekstrom, Goran; "Deep Earthquakes outside Slabs," Eos, 71:1462, 1990. (X1)

ES OUTER-CRUST ANOMALIES

Key to Categories

ESR PHENOMENA OF THE OUTER CRUST

Key to Phenomena

ESR0 Introduction

This section of the Catalog of Anomalies is concerned with what might be called the "larger problems" of geology. The problems are larger in two senses. First, the phenomena described here often involve planet-scale structures, such as the Andesite Line and the anorthosite belts. The other "larger" sense refers to the interrelationships of sedimentary strata; that is, stratigraphic inversions, the rhythmites, and the many cases where strata are apparently missing from the expected sequences. These "larger" aspects of stratigraphy are seldom treated in the textbooks. It turns out that the phenomena involved are not only fascinating but also unsettling.

Looking at the chapter as a whole, many of the doubts expressed in the other three geology volumes of the Catalog of Anomalies resurface here: (1) Was the earth's history dominated by catastrophic events rather than uniformity? (2) Is the geological time scale accurate? (3) Is the assumed pattern of biological evolution correct? (4) Is plate tectonics a correct model? (5) Are geological rhythms internally or externally generated? The list could be greatly enlarged; the point being made here is that geology contains many anomalies. The opportunities for further research are virtually unlimited.

ESR1 The Incompleteness of the Stratigraphic Record

Description. (1) The apparent gaps in the Stratigraphic Record due to missing strata, as determined by reference to the succession of geological periods (and finer subdivisions) established by the theory of evolution. (2) The very large apparent deficit of sedimentary rocks, based upon modern measurements of sediment-deposition rates and the time spans assigned to geological periods by radiometric methods.

Data Evaluation. Although the geological literature is forthcoming with many reports of unconformities, very few papers mention the remarkable incompleteness of the Stratigraphic Record. On the other hand, creationists have been verbose about gaps in the Stratigraphic Record; they have also produced the only systematic survey of stratigraphic gaps (based upon the scientific literature) that we have found to date. Rating: 2.

Anomaly Evaluation. A few small gaps here and there in the Stratigraphic Record could easily be explained away as due to erosion and/or cessations in deposition. However, the apparent gaps are so great in terms of time-span, volume, and geographical area, that an important anomaly may exist here. Some questions posed by these great gaps are: (1) Is the accepted radiometric time scale accurate? (2) Is the succession of geological periods, as determined by fossil content and the theory of evolution, really correct? Equivalently, is the development of terrestrial life envisaged by the theory of evolution correct? (4) Are the geological periods (established by fossil content) actually synchronous over the entire globe? These are among the most important questions we can ask of our science; therefore, the "gap" phenomenon is potentially very anomalous. Rating: 1.

Possible Explanations. (1) Radiometric time measurements, for reasons we do not yet understand, are grossly in error. Consequently, the geologists' time scale is in error. (2) The succession of life forms presented by the theory of evolution is incorrect; and the geological periods are incorrectly assigned. (3) The fauna that determine the geological periods have existed in times and places in ways that invalidate the concept of geological periods determined by evolution. (4) Admittedly, the most likely explanation, based upon what we know today, is that gaps in stratigraphy are due only to episodes of erosion and/or hiatuses in deposition.

Similar and Related Phenomena. Apparently inverted strata (ESR3); radiometric discordances (ESP12); radiohalo anomalies (ESP1); skipping in the fossil record (ESB12); biological anomalies that challenge the evolution paradigm (series B catalogs).

Examples

X0. Introduction and background. A "missing" sedimentary stratum in the Stratigraphic Record exists:

(1) Where adjacent strata possess fossil contents that differ appreciably, indicating the passage of a large amount of time, as measured by the evolutionary time scale. Generally, this means that we are restricted to saying that some geological period, such as the Ordovician, is missing. Geological periods have historically been defined and assigned on a time scale according to their fossil contents.
(2) Where adjacent strata possess appreciably different ages, as determined by radiometric dating. Radiometric dating, of course, is the technique geologists use to attach time markers on the Stratigraphic Record.

In this section, almost all missing strata are identified by the first method. The word "appreciable" is used above because our purpose here is to find large time gaps in the Stratigraphic Record. Obviously, the hiatus represented by the separation of annual varves in a clay deposit indicates only the cessation of deposition for a few months. This is hardly anomalous. We are searching for gaps measured in the millions of years.

The existence of an apparent gap in the Stratigraphic Record---and therefore the apparent passage of considerable time---can be accounted for in several ways:

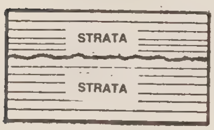
(1) Deposition of sediment ceased for for a long period of time, perhaps because the geographical region under scrutiny rose above sea level; the climate changed drastically, or some other major terrestrial event occurred.
(2) The sediments deposited during the supposed "time gap" were somehow eroded away without a trace.
(3) The fossil contents of the strata are not accurate indicators of the passage of time. A possible implication here is that biological development did not occur as currently envisaged.
(4) Radiometric dating is faulty.
(5) Conceivably, thrust faulting interposed exotic strata between properly sequenced strata. The Stratigraphic Record would thus be tainted timewise. (See ESR3.)

Unconformities and their significance. The nature of the contact between the strata on either side of a supposed missing stratum (or time gap) is important. If this contact is rough and/or nonparallel, we can usually conclude that geological forces, such as erosion, uplifting, and tilting, have been at work. The passage of time is also implied. Geologists apply the term "unconformity" to such situations. The two types of unconformities mentioned above are sketched in the accompanying illustration, and are designated as "disconformities" and "angular unconformities". A more-difficult-to-explain unconformity is the "paraconformity", in which there is no evidence of erosion, earthquakes, tilting of strata, or any other kind of time hiatus. At paraconformities, hundreds of millions of years seem to be missing without any attendant geological activity. This is anomalous indeed on the earth, which must be considered a

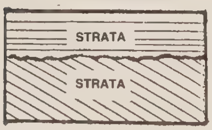
Eons	Eras	Periods	Epochs	
Phanerozoic	Cenozoic	Quaternary	Holocene	0.01
			Pleistocene	1.6
		Tertiary	Pliocene	5.3
			Miocene	23.7
			Oligocene	36.6
			Eocene	57.8
			Paleocene	66.4
	Mesozoic	Cretaceous		144
		Jurassic		208
		Triassic		245
	Paleozoic	Permian		286
		Carboniferous		360
		Devonian		408
		Silurian		438
		Ordovician		505
		Cambrian		570
Proterozoic				2500
Archean				3400+

The geological timetable. The beginning of each segment is given in millions of years before the present. The Carboniferous is often subdivided into the Pennsylvanian (320-286) and the Mississippian (360-320).

DISCONFORMITY



ANGULAR UNCONFORMITY



Sketches of two types of unconformities. In the disconformity, an age gap exists but the strata are parallel. The angular unconformity is characterized by erosion and tiling of the strata.

very active planet.

This problem of stratigraphic gaps is not a trivial one, for there seem to be more gaps than record in the Stratigraphic Record, when geological data are compiled for the entire earth. D. Ager commented on this in his book

The Nature of the Stratigraphical Record:

> "The sedimentary pile at any one place on the earth's surface is nothing more than a tiny and fragmentary record of vast periods of earth history. This may be called the Phenomenon of the Gap Being More Important than the Record." (R12)

The implications depend upon the theory being defended. Some students of the Stratigraphic Record view missing strata as proof that uniformitarianism is an incorrect picture of the earth's past. To illustrate the catastrophists' position, we quote from A.W. Mehlert, who in turn draws from H.H. Howorth, a proponent of universal flooding.

"The next virtually fatal problem for uniformitarian geology is the presence of thousands of cases of deceptive conformities (paraconformities) in the understrata involving both continental and marine deposits. These cases, some of them covering vast areas occur when two deposits, allegedly separated by many millions of years, lie smoothly together with not the slightest sign of erosion on the lower beds. I will let Sir Henry Howorth, a non-creationist geologist of 80 years ago, eloquently describe his thoughts on paraconformities in his 1905 work Ice or Water? (pp. 330-331)

'The absence of the erosive agency of water, as manifested in cutting valleys and gorges in the under strata of the earth, is fatal to the theory that each formation has successively emerged from the sea and become the surface of the habitable world...What we want to see is a plain instance of valleys excavated and mountains formed in the ancient strata of the earth as we find them existing in the present day...until then we take leave to reject the theory...the parallelisms of the beds over large regions of the earth stand in complete opposition (to the notion that the under strata have ever been the surface of the earth for indefinite periods.)'" (R20)

Modern geologists, however, consider missing strata as only a minor inconvenience. A.N. Strahler, after discussing the two giant gaps in the Grand Canyon's sequence of strata, commented: "Although this long interval of freedom from tectonic activity is remarkable, it poses no special problem to mainstream geology." (R23)

In the following entries, we shall see that the "problems" are not entirely negligible, particularly in the Grand Canyon. (X4)

Finally, in the interest of completeness, we should not set aside the possibility, remote though it may seem, that missing strata might indicate basic flaws in geochronology and/or the way in which we believe life of earth developed. (WRC)

X1. Missing Precambrian crust and ophiolites. The oldest rocks are those of the Precambrian---650 million years and older. These rocks are part of the Stratigraphic Record, but the great bulk of our discussion below will be confined to the most recent 650 million years. Thus, it is only fitting that we devote a little space here to the Precambrian, which encompasses three-fourths of the earth's history.

Precambrian geological research is difficult because of the age of the rocks and the effects of the powerful chemical, physical, and thermal forces to which they have been exposed. Even so, it quickly becomes apparent that much of the Precambrian record is missing, especially that part prior to 2 billion years ago. Not only is much of the so-called Archean crust gone but so are most of the ophiolites (pieces of oceanic crust) that mainstream theory demands be present.

The missing Archean crust. We begin here with a quotation from S.W. Carey's Theories of the Earth and Universe.

"Dr. Andrew Y. Glikson, of the Australian Bureau of Mineral Resources, has studied intensively the petrology and geochemistry of the most ancient rocks---the foundation platforms older than 2 billion years on which later systems of strata were deposited. These make up about 80 percent of the present-day continental foundations and add up to about a quarter of the earth's crust. Glikson asks: What was the nature of the crust that occupied the other three-quarters of the earth's surface 2 billion years ago?" (R24; see also R15 and R16.)

Glikson reviewed four possible solutions to the problem of the missing crust. To illustrate, he considered the possibility that it had been subducted, but concluded that this was unacceptable geochemically. His other ideas met similar fates. He finally concluded that the answer must be that the "missing" crust never existed in the first place. This solution is consistent with the expanding earth hypothesis, for which S.W. Carey is the leading champion.

Missing ophiolites and flysch. Once again, we apparently have large pieces of the earth's early integument missing ---at least it is missing if mainstream models of the planet's early history are correct. S.W. Carey also believes that the missing ophiolites and flysch are consistent with the expanding earth hypothesis. In his book (R24), Carey quotes K. Crook in this matter.

"Ophiolites and flysch, two mobile belt associations indicative of the oceanic realm of the earth's crust, are well represented in the rock record of the last billion years. Their abundances, expressed as area of outcrop per million years, decrease exponentially with increasing age during this interval, in a manner consistent with predictions based upon the probability of their preservation. Although ophiolites are virtually unreported from the one billion to 2.5 billion years rock record, possible Archean analogues, the greenstone belts, are represented throughout the pre-2.5-billion-year record. Similarly, flysch is rarely reported from the one- to two-billion-year part of the record, but is not uncommon in terrains older than 2.0 billion years. These abundance patterns depart so grossly from predictions based upon preservation potential as to demand an explanation." (R24)

The "expanding earth" is not the only hypothesis advanced to explain these missing sections of the Precambrian. For example, E.M. Moores has written: "To account for the lack of preservation of ophiolites (fragments of oceanic crust and mantle) in old orogenic belts (age 1000 to 2500 million years), a hypothesis proposes that the magmatic ocean crust formed during sea-floor spreading was thicker during the cited time interval. This thickening led to reduced contrast between the elevation of continental and oceanic regions and to greater average flooding of the continents." (R21)

Some ophiolites have been found in unexpected places; viz., Wyoming. The modern view is that such wayward bits of oceanic crust have been transported from afar and plastered on the continental masses. See ESR9 under "terranes".

X2. What portions of the Stratigraphic Record may be found missing? In actuality the answer is: Any or all!

Taking "all" first, the existence of giant gaps was recognized by many early geologists. In 1864, J.J. Bigsby wrote as follows.

"Throughout by far the greater part of the extensive countries of Norway, Lapland, Sweden, and Finland, Quaternary Diluvium and Northern Drift lie directly on Laurentian and Huronian rocks; little or no deposition having taken place there (through 25° of longitude and 13° of latitude) during the vast interval of time between that of the contiguous formations. Marks of denudation are many and powerful here; and though there are patches of younger strata, they do not require notice from us.

On the opposite coast of North America all this is repeated, through Labrador and Canada to beyond the Upper Mississippi River, in a broad belt of rugged land 2000 miles long, where no Mesozoic nor old Tertiary rocks, loose or fixed, have been met with, though often looked for. From this block of older metamorphic formations another broad band of the same antiquity, sprinkled with sand, gravel, and boulders, runs from Lake Superior into the Arctic Ocean, through Rupert's Land, for 1500 miles. Messrs. Foster and Whitney also remark that 'Between the Northern Drift of the south side of Lake Superior and the Devonian there are no deposits, but an immense gap in the series of formations. Of the condition of the ancient surfaces we have no evidence; but we now see it covered with stratified drift of sand and clay, sometimes 1000 feet above the present level of the lake.'" (R1)

We may wonder how much of these huge gaps is due to lack of sedimentation and how much to erosion of deposits, but in truth there is no formidable anomaly here. Well-recognized geological explanations are available, although perhaps they are stretched a bit. In fact, eons of erosion by water, ice, and wind can in principle denude any landscape down to the most ancient rocks. (WRC)

G.M. Price, an early creationist went straight to the heart of the missing-stratum problem by formulating two "facts", the second of which is the more important.

"For the Fact Number One, which I have chosen as the subject of this chapter, is the now well-established principle that any kind of fossiliferous rock whatever, even 'young' Tertiary rocks, may rest upon the Archean or Azoic series, or may themselves be almost wholly metamorphosed or crystalline, thus resembling in position and outward appearance the so-called 'oldest' rocks." (R3)

Not only can any stratum be among the

missing, but there may be no superficial way to verify that a gap does indeed occur. This situation was explained by Price in his Fact Number Two: "Any fossiliferous formation whatever may rest conformably upon any other 'older' fossiliferous formation." In elaborating on this "fact", Price clearly pinpoints the anomaly under scrutiny in this section.

"The lower may be Devonian, Silurian, or Cambrian, and the upper one Cretaceous or Tertiary; and thus, according to the theory, millions on millions of years must have elapsed after the first, and before the following bed was laid down. But the conformity is perfect, and the beds have all the appearance of having followed in quick succession. Sometimes, too, these age-separated formations are lithically the same, and can be separated only by their fossils! A still more amazing fact, from the standpoint of current theory, is that these conformable conditions are often repeated over and over again in the same vertical section, the same kind of bed reappearing alternated with other beds of an entirely different character; that is, a certain kind of fossiliferous stratum may be found interbedded several times in a manifestly undisturbed series of very different beds." (R3)

With these generalities in hand, we now repair to the task of providing specific examples of missing strata.

X3. The Appalachians. A striking paraconformity in Kentucky was made famous (to geologists) through a photograph taken by the noted stratigrapher C. Schuchert and published in 1910. A.N. Strahler described this photo as a paraconformity "...separating limestone beds of Middle Silurian age from those of Middle Devonian age; it is shows the paraconformity as a straight, horizontal line, almost perfectly parallel with the bedding planes. Elsewhere in the Appalachian region, the same time gap is occupied by strata measuring over 1000 m in thickness." (R23)

This same photo was discussed in detail by E.M. Kindle in 1912. He stated that the photograph illustrated "...the complete absence of evidence of unconformity between the two formations, aside from the age of their faunas, and our dependence upon the discordance in the superposed faunas for our knowledge of the hiatus between them." (R2)

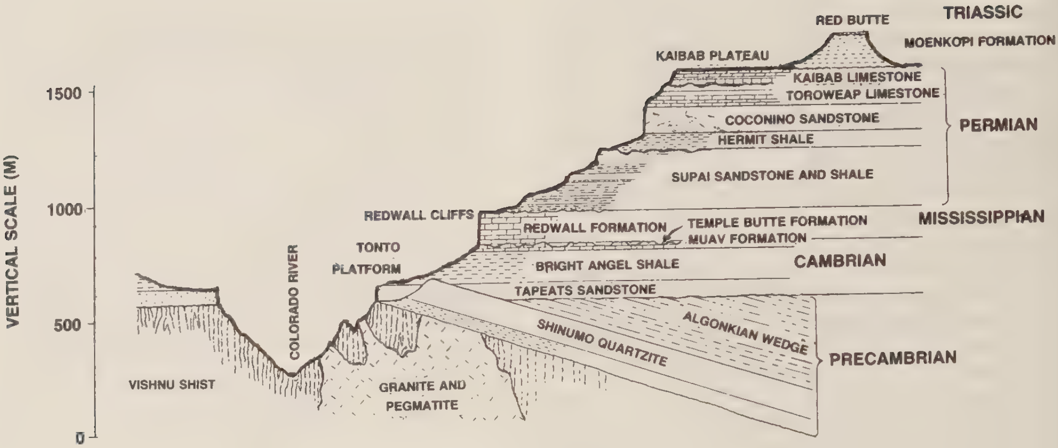
Kindle, however, also claimed that physical evidence of the unconformity did exist elsewhere. He also stated that the paraconformity was between the Chattanooga shale and a Devonian limestone. From Kindle's paper we would have to conclude that this paraconformity, though striking in some localities, is only a run-of-the-mill unconformity elsewhere. (WRC)

X4. The Grand Canyon. The Grand Canyon is a Mecca for geologists. The mile-deep incision cuts down through hundreds of millions of years of strata. Hiking down the trail to the bottom, one passes back through time, age after geological age. Most sedimentary beds are laid down neatly and horizontally. However, about half way down to the Colorado River, one encounters the following sign:

> "AN UNCONFORMITY
> Rocks of Ordovician and Silurian Periods are missing in Grand Canyon. Temple Butte Limestone of Devonian age occurs in scattered pockets. Redwall Limestone rests on these Devonian rocks or on Muav Limestone of much earlier Cambrian Age." (R22)

Over 200 million years of sediment are missing at this spot, which is indicated on the accompanying sketch. Another 20 million years are absent higher up. C. Burdick described both hiatuses in more detail in the following paragraphs.

"The Supai formation apparently lies conformably upon the Redwall, 550 feet of Mississippian limestone. [See sketch] By conformably I mean that no apparent angular discordance exists between the two formations that might suggest a time interval between the periods of deposition. However, we are told that such a gap exists, a gap of perhaps some 20,000,000 years of Pennsylvanian time, so deducted because of the lack or non-existence of Pennsylvanian fos-



A stylized cross section of Grand Canyon strata. (Based on A.N. Strahler's drawing, R23, X4)

sils.

"As one descends deeper into the gash in the earth, he passes 550 feet of Redwall Mississippian limestone dyed red by the overlying red Supai formation. This formation lies apparently conformably upon the Cambrian Mauve [sic] limestone. By conformably we mean that the two formations lie one upon the other like leaves in a book, with no apparent angular discordance due to tilting of the strata and subsequent erosion, which one would expect if a time gap between episodes of [deposition] had taken place.

"The Ordovician, Silurian and Lower Devonian are missing at this place in the Canyon, in fact the first two are missing over most of Arizona. Let us contemplate the significance of such an awesome hiatus, of some 100,000,000 years. In our own lifetime we can measure the rise of certain shorelines and the sinking of others. Twenhofel remarked that there is hardly a place on earth that is really stable." (R8) Most geologists assign 200,000,000+ years to this gap. (WRC)

Mainstream geologists do not deny these gaps. Here, we add some remarks by A.N. Strahler with respect to this gap.

"In this case, the disconformity represents an enormous time gap. Between the Cambrian and Mississippian periods lie the Ordovician, Silurian, and Devonian periods, which total about 245 m.y. It seems hard to imagine, but the parallelism between strata above and below the disconformity requires us to conclude that throughout that vast span of time the earth's crust in this region was not subjected to tectonic activity that elsewhere repeatedly deformed crustal rock by faulting and folding. We can only conclude that this region was part of a stable continental margin, far from any subduction boundaries where collision activity might occur and from areas of the continental lithosphere where rifting was in progress." (R23)

But is such a conclusion reasonable? It has to be considered so if our view of the development of the earth and its biological cargo is to remain intact. (WRC)

X5. The Colorado Plateau. An extensive unconformity separates the Permian and Triassic ages on the Colorado Plateau, as well as at many other locations on our planet. This 245-million-year-old unconformity "apparently" does not mark the omission of a great thickness of strata (and the time it took to deposit it), rather it was a major turning point in the history of life. The Permian-Triassic transition is marked by mass extinctions; viz., the trilobites. It was in the words of S.J. Gould "a time of great dying". After the massive extinctions, the geological clock moved to the Triassic, and life reflowered. But, something of great importance happened on the earth at this juncture; and we do not know what it was and how long it lasted. We do not know if sediments were deposited and subsequently eroded away. See ESB1, in another volume, for more on this crisis in the history of life.

This Permian-Triassic boundary is, in some parts of the world, very poorly marked. Geologically, the two periods seem to blend into one another, despite what happened to the biosphere. N.D. Newell has remarked on this fauna-delineated boundary as it appears on the Colorado Plateau.

"Physical evidence of an unconformity at the era boundaries may be obscure or equivocal at some localities. For example, the Permo-Triassic rocks are approximately parallel over an area of hundreds of thousands of square miles on the Colorado Plateau (Kaibab-Moenkopi formations) and in the northern Rocky Mountains (Phosphoria-Woodside). At many outcrops the contact between the two systems is structurely concordant and apparently conformable. Regional studies, however, show that an unconformity separates the Permian and Triassic rocks probably throughout all of this region." (R2) See also X6 for a similar occurrence.

X6. The Salt Range, Pakistan. A situation analogous to that just described for the Colorado Plateau prevails in Pakistan's Salt Range. Despite the striking faunal changes across the Permo-Triassic boundary, numerous investigators confirm: "that there is no evident physical break between the Permian and Triassic rocks in the Salt Range." (R7)

X7. Two important Canadian paraconformities. The two examples below cited by G.M. Price (R10) are supported by quotations from reports of the Canadian Geological Survey.

Near Banff, Alberta. "East of the main divide the Lower Carboniferous is overlaid in places by beds of Lower Cretaceous age; and here again, although the two formations differ so widely in respect to age, one overlies the other without any perceptible break, and the separation of one from the other is rendered more difficult by the fact that the upper beds of the Carboniferous are lithologically almost precisely like those of the Cretaceous [above them]. Were it not for fossil evidence, one would naturally suppose that a single formation was being dealt with." (R10) Reference: Canadian "Annual Report," Geological Survey, New Series, 2, Part A, 8.

Near Lake Athabaska, Alberta and Saskatchewan. "There is a large area near Lake Athabaska, Canada, where a Devonian limestone is conformably covered by Cretaceous beds. The 'remarkable persistence' of this 'deceptive' conformity, according to an officer of the Canadian Geological Survey, extends in one direction for fully 150 miles; and yet, over this wide area, according to this very competent authority, 'the vast interval of time which separated the two formations is, so far as observed, unrepresented either by deposition or erosion.' Indeed, this same succession of strata, Cretaceous upon Devonian, extends nearly to Lake Manitoba, some 500 miles away, though it would be quite unreasonable to expect even the most honest conformity to extend to any such distance." (R10) The source given by Price for the example is also the Annual Report of the Canadian Geological Survey, New Series, Vol. 5, Part D, p. 52.

The situation in the above two examples resembles that at the Permo-Triassic boundary, as sketched in X5 and X6, except that here there are definitely large blocks of missing time, according to current geological thinking. (WRC)

X8. Indian Ocean sediments. Until the 1970s, oceanographers believed that sedimentation in the oceans was essentially continuous. But cores recovered during the Deep Sea Drilling Project (DSDP) revealed missing sediments in virtually all of the oceans. The Indian Ocean, in particular, is noted for its many sedimentary gaps, as in the following quotation.

"Sediments spanning 'vast intervals of geologic time'---as much as 50 million years---are completely missing from many areas of the Indian Ocean. In seven of the eight deepest holes, there was a gap in the sediments between 40 million and 20 million years old. A gap of about the same age and duration had been found by Leg 21 scientists off the east coast of Australia." (R11)

Later drilling in the Indian Ocean demonstrated that there were many gaps and that some were ocean-wide in extent. They were concentrated in the Oligocene, early Tertiary, and late Cretaceous periods. (R14) The authors of R14 thought the gaps to be best explained by appealing to climatic events in Antarctica, which subsequently altered the circulation patterns of the Indian Ocean.

The situation may be no better in the other oceans. Drilling in the South Atlantic has found barely half of the sedimentary record expected for the past 125 million years. (R18)

X9. The incompleteness of the Stratigraphic Record: The Sedimentation Rate argument. Up until now, we have concentrated on specific unconformities, paraconformities, and their implied gaps. There is, though, a convincing type of argument that leads to the conclusion that the Stratigraphic Record we chip away at with our geology hammers actually represents only a few percent of the total span of geological time. This approach involves estimating the amount of time required for the deposition of specific strata by applying the deposition rates measured at appropriate present-day sites. T.H. van Andel has expounded eloquently upon this subject.

"For years I have been intrigued by the result of such estimates. In Wyoming, a sequence of early Cretaceous sandstones and shales closely resembles the coastal sediments of the present Gulf of Mexico. Applying the appropriate rates of deposition we find that a mere 100,000 years would suffice to produce the entire sequence. Yet the stratigraphical interval occupied by the deposits is quite firmly known to encompass about 6 million years. We may repeat the experiment elsewhere; invariably we find that the rock record requires only a small fraction, usually 1 to 10 per cent, of the available time, even if we take account of all possible breaks in the sequence." (R18)

Further applications of modern sedimentation rates to ancient strata led van Andel to these conclusions: "Thus it appears that indeed the geological record is exceedingly incomplete, and that the incompleteness is greater the shorter the time span at which we look. ....The geological record may thus be a record of rare events separated on any time scale by numerous and long gaps." (R18)

A.N. Strahler has adopted a more uniformitarian scenario to fill up the admitted great gaps implied by the sedimentation-rate argument. Strahler believes that the time gaps are filled by innumerable brief cessations of sedimentation, perhaps only a few years or a century or two long. In geology these tiny hiatuses are called "diastems". (R23)

Spans of geological time are now measured by radiometric methods, rather than sedimentation rates. One cannot compress geological time without overthrowing the tenets of radiometric chronology. Further, one must ask what, if anything, happened during the 90% or so of geological time for which we have no record. (WRC)

X10. The incompleteness of the Stratigraphic Record: The Missing Period argument. The sedimentation-rate argument offered in X9 tells only part of the "gap" story---the part concerned with vanished or undeposited volumes of sediments. In addition to the attributes of thickness, each stratum also possesses the properties of geographical extent and fossil content. It is the latter property, of course, that allows us to assign each stratum to a geological period, such as the Permian or Cretaceous. Absolute dates are assigned radiometrically. When the earth's geological formations are mapped globally, by geological period, an astounding patchwork appears. It is a patchwork with more holes than fabric! The various geological periods comprising the classical Stratigraphic Record are distributed spottily and sparingly on world maps. Indeed, there is virtually no place on earth where all periods are represented. The great bulk of the Stratigraphic Record has either been removed or was never deposited in the first place. (Complete sequences have been reported from the Bolivian Andes and Nepalese Himalayas, although there are doubts even at these locations.)

It is interesting, but perhaps not surprising, that the best review of this problem was prepared by a creationist, J. Woodmorappe [a pseudonym]. Backed with 97 papers and books from the scientific literature, Woodmorappe has generated 15 maps that indicate where each major geological period has been reported as being present or not present. We have room here for only two of these maps---the Permian and Triassic. In conjunction with the maps, it is appropiate to present Woodmorappe's abstract.

"This article is a systematic and quantitative demonstration of global distributional tendencies of the evolutionary-uniformitarian geologic column.

"Maps have been drawn to show the worldwide distributions of all ten geologic periods on all seven continents, and such maps have also been drafted to show complete segments of the geologic column in place.

"Calculations have been performed to measure successional tendencies of geologic periods over the earth. For example it has been found that two-thirds of the earth's land surface has 5 or fewer of the 10 geologic periods in place, and only 15-20% of the earth's land surface has even 3 geologic periods appearing in 'correct' consecutive order.

"These and similar findings have been briefly related to the Creationist-Diluvalist paradigm." (R19)

It is vital to add that Woodmorappe's maps show only the continents. It is well-recognized that almost all of the sediments preserved in today's oceans are very young---less than 250 million years old. Woodmorappe-type maps of the oceans prior to the Jurassic would be solid black. (WRC)

A vertical profile. Woodmorappe has gone a step further in his analysis. He provides us with a table in which he notes for each period the area-percentage for which this period is in direct contact with each older period. We reproduce here the figures for the Permian period:

Permian/Carboniferous	76.3%
Permian/Devonian	10.5
Permian/Silurian	6.08
Permian/Ordovician	1.10
Permian/Cambrian	2.76
Permian/Precambrian	3.30

Obviously, most of the Permian strata lie directly on the Carboniferous, as they should---but not always. In fact, the table confirms what G.M. Price maintained earlier in this section: missing strata are common in the Stratigraphic Record, and a younger period's strata may be found on the strata of any older period. (We come to grips with inverted strata in ESR3.) Of course, Woodmorappe's table does not show the percentages of the contacts that are conformable and unconformable. It is also obvious that Woodmorappe's maps will change as geological mapping proceeds.

What does it all mean? Woodmorappe, being a scientific creationist, takes the position that his results call into question the very existence of geological periods and expose, as well, the fiction of a complete Stratigraphic Record, with its time-wise orderly development of life. The Stratigraphic Record is, he says, only an artificial construct designed to support the evolutionary-uniformitarian paradigm. (R19)

Such sweeping conclusions are anathema to the scientific community. But, one must admit that Woodmorappe's research does engender questions: Could Cretaceous sediments have been laid down some place on the globe, while Tertiary sediments were accumulating elsewhere---at the same time? Radiometric dating can, in principle, answer such questions; but has it done this in a convincing number of cases? Do the black areas on Woodmorappe's maps, representing absent sediments, indicate erosion or lack of deposition? Woodmorappe makes the statement that in the tens of millions of years allowed each geological period some sediments

Map 6. Distribution of Permian strata. (After J. Woodmorappe)

Map 7. Distribution of Triassic strata. (After J. Woodmorappe)

should have accumulated in each. If so, could erosion have swept whole continents clean? And where did all these sediments go? Mainstream science believes that its armory of fossil succession, radiometric dating, and episodic erosion and sedimentation, caused by changing sea levels and the rising and subsiding of land are more than sufficent. It is a matter of opinion whether these accepted processes can cope with the sheer number and magnitudes of the gaps in the Stratigraphic Record. In the compiler's view, the gaps are so large---timewise, volume-wise, and area-wise---that these mainstream paradigms must be reconsidered. (WRC)

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ESR2 Lateral Variations in Strata

Description. Anomalous lateral variations in the character of sedimentary strata, such as: (1) radical and/or incompatible changes of facies; (2) fossil-content variations that normally betoken great age differences; (3) large-scale splitting of strata; and (4) interfingering of diverse strata.

Background. Normally, one thinks of lithological and fossil-content changes as occurring in the vertical dimension, which the law of superposition states is the direction in which temporal changes should take place. But no stratum is infinite in extent; each pinches out or terminates somewhere. A few of these "edge effects" are curious enough to catalog.

Data Evaluation. Very few examples of lateral variations have been found so far. Rating: 3.

Anomaly Evaluation. Most lateral phenomena are readily explained in terms of tectonic movements and changing environments. The exceptions are those which call into question the reliability of fossils as time markers in geology. For fossil content (and therefore geological time) may change markedly laterally in a sedimentary formation; also, strata differing in age by hundreds of millions of years may interfinger and intergrade as if no time gap existed. Since the use of fossils as time markers is central to geological thinking, such phenomena are highly anomalous. Rating: 1.

Possible Explanations. The indiscriminate use of fossils for geological dating may lead to errors because: (1) The real age of strata may vary appreciably over their horizontal extent; and (2) Organisms, customarily thought to be of different ages, may have existed at the same time in separate environments. Of course, neither of these possibilities is considered viable by mainstream geology.

Similar and Related Phenomena. Radiometric dating discordances (ESP1, ESP12); tektite age paradox (ESM3-X13); tektite recency paradox (ESM3-X18); polystrate fossils (ESX1).

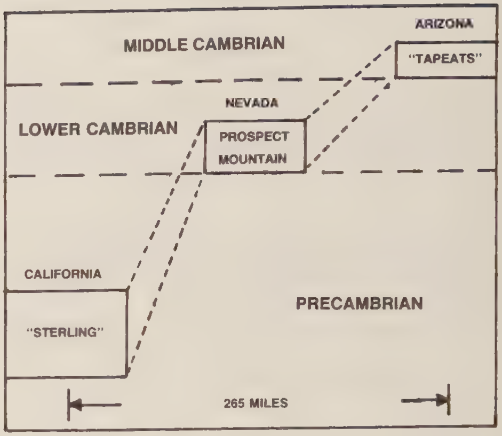
Examples

X1. Intergrading of diverse rocks. It is not surprising when coarse sandstone grades into fine sandstone and then perhaps into siltstone. The ability of water to transport particles of rock obviously varies laterally as the water's velocity changes. However, when one type of sedimentary rock grades into a radically different type of rock, a special explanation may be required.

Coal into dolomite. A. Strahan provided the following description of intergrading at Wirral Colliery, Great Britain.

"The author was informed by Mr. N.R. Griffith in 1900 that the Seven-Feet Seam of the Wirral Colliery had been found to pass into stone of an unusual character. For a distance of 1800 yards from the shaft this seam was good, and about 4-feet thick. A little farther in, bands of stone from 1 to 10 inches thick made their appearance in it, and gradually increasing in thickness, these bands eventually constituted the whole seam, the last traces of workable coal disappearing at 250 yards from the point where the change first began. The boundary of the barren area has been found for a distance of 1480 yards and it runs north and south. The stone is at first black, but after weathering it becomes grey, and displays curious structures, some of which are pisolite, or mammillated structures, the intervening spaces being filled with coaly matter. One specimen displays woody tissue filled with dolomite. Analyses by Dr. W. Pollard yield from 13 to 18 per cent of magnesia. The phenomena are not those of a 'wash-out,' as there is no sign of erosion, but there is proof that the dolomite was formed in almost motionless water, and the conditions appear to have been those under which a tufa would form. It appears to have been formed on a spot to which clastic material scarcely gained access, and which was reached even by vegetable matter in scant quantity and in a finely divided condition." (R2; R1) While the exact environment of deposition is unknown, there does not seem to be anything anomalous here. (WRC)

X2. Temporal transgression. It is commonly thought that a stratum is laterally synchronous; that is, all of the sediment at a given level was deposited at about the same time over the entire horizontal extent of the stratum. The idea that the same formation could belong to more than one geological period seems heretical, but such does occur.



A so-called "temporal transgression. See text for description. (X2)

A Cambrian-Precambrian lithogenetic unit. To illustrate the phenomenon of temporal transgression, H.E. Wheeler and E.M. Beasley selected the most extreme case in their experience. The unit chosen was the Bright Angel shale (exposed in the Grand Canyon) and its lithogenetic equivalents in a 12,000-square-mile triangle stretching into southern California and southern Nevada. The Abstract from their 1948 paper reveals the basic nature of the phenomenon as well as its implications.

"The Bright Angel group of the southern Great Basin region is defined as consisting of the predominantly argillaceous strata which lie between the underlying Prospect Mountain quartzite and the overlying Middle Cambrian limestones. This lithogenetic unit is shown to range in age from partly pre-Cambrian in the Nopah Range of southeastern California to entirely Middle Cambrian in the Grand Canyon of Arizona. The Bright Angel group illustrates the fact that the problems of stratigraphic classification are four-dimensional and, as such, are not amenable to treatment by the conventional dual system of stratigraphic nomenclature.

"The fact that rock units and unconformities may vary in age from place to place is determined as the sole factor demanding (1) a three-fold nomenclatural system, and (2) abandonment of the concept that erosional breaks may serve as time-stratigraphic boundaries. This variation in age of lithogenetic units is recognized as a fundamental truth in stratigraphy, nearly equal in significance to the laws of superposition and faunal succession, and is appropriately designated therefore as the principle of temporal transgression." (R3)

One can easily conceive how a lithogenetic unit could be deposited over a very long period of time, with the locale of deposition moving steadily laterally in response to tectonic and climatic changes, In other words, sediments derived from the same source could be laid down in different areas at different times. The time of deposition in the study at hand was determined by fossil content. If one wishes to be heretical, one could maintain that the Bright Angel group above was actually deposited everywhere at the same time, but that different fauna were prevalent in different areas. Such a supposition of course denies the law of faunal succession. This possibility should not be rejected out-of-hand, even though geological dating via index fossils would be compromised. Presumably, radiometric dating could clarify such situations in the field. Philosophically, though, this sort of thinking is not permissible! (WRC)

X3. Stratum splitting. Another type of lateral variation occurs when a stratum splits, becomes separated by a different type of rock for a while, and then recombines. Lenses of exotic sedimentary material are quite common in geology. One can imagine how temporary flooding or some other environmental change could interrupt sedimentation with a limited injection of extraneous material. This sort of explanation becomes strained in some instances.

Remarkable splitting in English coal seams. In Staffordshire, England, one coal bed, 25 feet thick, splits into eight seams. The total thickness of the coal and the intervening beds of exotic material is 390 feet. (R4)

X4. Interfingering of strata. The interfingering of different types of sedimentary rocks is not uncommon. To illustrate, a transgressing or regressing sea will leave interfingered marine and terrestrial sediments. Not all interfingering is so easily accounted for.

At a depositional hiatus in the Grand Canyon. A 200-million-year hiatus is said to exist in the Grand Canyon, where the Mississippian Redwall limestone rests directly upon the Cambrian Muav limestone. (See ESR1-X4 for details.) The accompanying sketch shows how the two formations laterally grade into each other, with much interfingering. (R6)

It is difficult to see how such an intimate relationship could exist if the two limestones were deposited 200 million years apart. Situations like this call into question the accuracy of fossil time markers. (WRC)

A bizarre case from the Andes. "The [sketch] shows a Pleistocene black-ash bed in tuffaceous lacustrine strata, in a road cut north of Quito, Ecuador...The problem is to explain the displaced upper part of the black ash in the distorted horst block. (Hint: bedding-plane slip." (R5)

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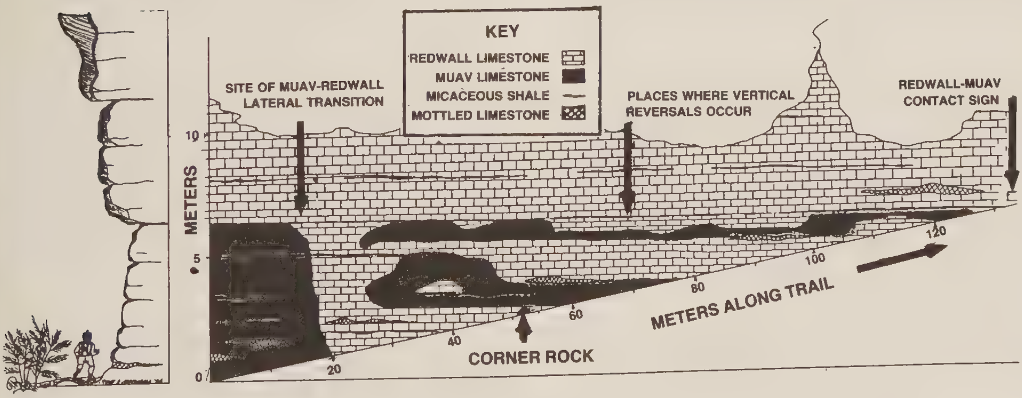

A diagram of the Grand Canyon strata near the Redwall Limestone-Muav Limestone contact, on the North Kaibab Trail. Although the two limestones are separated by 200 million years, they intergrade and intertongue. Vertical distances are exaggerated four-fold. (After R. Marshall, R6, X4)

A curious displaced section of a bed of black ash in the Andes. (X4)

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R4. Kelly, Allan O., and Dachille, Frank; "Coal and Oil," Target:Earth, Carlsbad, 1953, p. 216. (X3)
R5. Hill, Mason L.; "Puzzle from the Andes," Geotimes, 26:12, November 1981. (X4)
R6. Waisgerber, William, et al; "Mississippian and Cambrian Interbedding: 200 Million Years Hiatus in Question," Creation Research Society Quarterly, 23:160, 1987. (X4)

ESR3 Apparently Inverted Strata

Description. Older rocks superimposed upon younger rocks, as determined by the fossil contents of the rocks and/or radiometric dating. In practice, fossil content is almost always the sole factor used in assigning a rock formation to a specific period in the Stratigraphic Record.

Background. The Law of Superposition requires that younger rocks be deposited upon older rocks. If an age inversion is found, mainstream science insists that a "geological solution" be found, such as an overthrust, rather than a "biological solution" wherein the sequence of life established by evolutionists is challenged. Creationists, who question the theory of evolution on other grounds, too, naturally prefer the biological solution. The interpretation of inverted strata, therefore, has been a controverted issue for most of the 1900s. In this context, it should be mentioned that mainstream scientists do not deign to recognize the biological solution as a viable alterative!

Data Evaluation. Inverted strata are mentioned frequently in the scientific literature, but only as secondary attributes of overthrust sheets, not as the primary observable. Extensive literatures exist on famous exposures of inverted strata, such as Heart Mountain, the Lewis Overthrust, etc. Rating: 1.

Anomaly Evaluation. As just pointed out, mainstream science automatically assumes that inverted strata are secondary characteristics of overthrust faults. This is equivalent to assuming a "geological solution" is the only one available. The anomalousness of inverted strata, therefore, depends upon how reasonable the geological solution is. The geological solution, it would seem, is challenged by overthrusts that are thousands of square miles in area and consist of rock sheets thousands of feet thick that have pushed tens of miles over adjacent strata---and with little if any evidence of said motion.

Geologists recognized the "size problem" early on, and called it the "mechanical paradox". This paradox arises because simple mechanical considerations show that a thick sheet of rock would be crushed by tectonic forces long before it began to slide over adjacent strata. In recent years, the mechanical paradox has not been as formidable as it once was due to: (1) the possibility that pore-water pressure might, in some instances, act like a hydraulic jack and help to reduce the coefficient of friction; and (2) an attractive theory of thrust faulting based upon the propagation of dislocations in which friction is of little importance. The mechanical paradox thus seems diminished, strengthening the geological solution to inverted strata and greatly weakening the biological solution.

A few problems remain: (1) How can some fault contact zones be so sharp and "deceptive"? (2) How did massive outliers, such as Chief Mountain, survive the erosive forces that obliterated so much of some thrust sheets? (3) How were the postulated tectonic forces confined to such restricted sets of strata? Rating: 2.

Possible Explanations. (1) Overthrust faulting is a reasonable explanation. (2) Much less likely, the theory of evolution is faulty.

Similar and Related Phenomena. Missing strata (ESR1); terranes (ESR9); cyclothems (ESR5); challenges to the theory of evolution (series B Catalogs).

Examples

(See ESR9 for "terranes".)

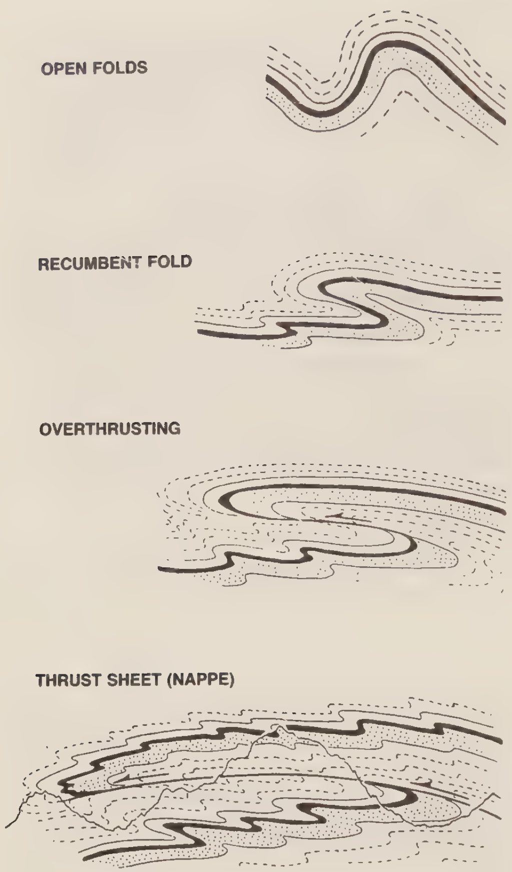
X0. Introduction and background. The Stratigraphic Record not only displays gaps, as delineated in ESR1, but also an even more remarkable phenomenon: "inverted strata". An inversion occurs in the Stratigraphic Record when older rocks are found superimposed on younger---say, Permian on Cretaceous, as determined by the fossil contents of the rocks. Mainstream science will not, at present, accept the possibility that the sequence of life forms envisaged by the theory of evolution might be incorrect. Thus, the order-of-appearance of geological periods is sacrosanct. The reality of inverted strata has therefore forced geologists to devise geological processes that create inversions of strata.

At least three reasonable scenarios have been generated:

(1) Overthrust faulting, in which tectonic forces cause strata to shear and slide over adjacent strata. (See figures.)
(2) Recumbent folding, in which tectonic forces create a fold in the strata that falls forward upon itself, like a wrinkled carpet.
(3) Terrane superposition, in which slabs of strata brought from distant sedimentary deposits by the forces active in continental drift are plastered over local strata.

How widespread are the inverted strata? Small overthrusts (or areas of inverted strata) are ubiquitous. Even large areas, covering thousands of square miles are not rare. For background on the major occurrences, we quote from the Introduction of a 1918 paper by R.T. Chamberlin and W.Z. Miller.

"...field studies in the last few years have brought to the attention of geologists impressive evidence of the prevalence and the great importance of what may well be called a different genus of fault, namely, the great low-angle overthrust. Its generic characteristics are the very low inclination of its fault plane and the extraordinary horizontal displacement often attained. Such low-angle overthrust faulting has been well described, as it is strikingly shown in the Northwest Highlands of Scotland, where the Moine, Ben More, Glencoul, and other remarkable thrusts form classic examples of the genus. In the extreme north of Sutherland the various rock groups overlying the Moine thrust plane can be shown to have been driven westward for a distance of ten miles. Horizontal shiftings of comparable magnitude occurred along the Ben More, Glencoul, and other planes of thrusting which lie beneath the Moine thrust and add to the remarkable nature of the phenomena.



Various degrees of overturning and overthrusting. (After A.N. Strahler, R54, X0)

Though since thrown into gentle folds, in many places it is clear that these planes of slippage were originally not far from the horizontal. In some other portions of the British Isles analogous phenomena have been observed.

"Similarly, in Scandanavia the very intense Caledonian deformation manifested itself in horizontal overthrusting of astonishing magnitude. The vertical displacement is slight, but the horizontal slip is measured in tens of kilometers.

"In the Southern Appalachian Mountains the Rome and Cartersville overthrusts run parallel to each other for over 200 miles. They are thought by Hayes to show horizontal displacements of not less than 4 miles and 11 miles respectively, and possibly much more. The inclination of the fault planes is here frequently as low as 5°; it is rarely more than 25°. The steeper portions of the plane as now seen are largely the result of subsequent warping. Farther north, in Tennessee, a possible continuation of the Cartersville thrust is the Buffalo Mountain fault which, according to Keith, was a low-angle overthrust whose original displacement along the shear plane was at least 20 miles. Subsequent folding and faulting have so disturbed this fault plane that its original inclination cannot be very closely determined.

"More to the north, the earlier Taconic revolution also developed low-angle overthrusts. Of these may be noted the Great Western fault of eastern New York, the St. Lawrence and Champlain fault, which runs from Vermont to the city of Quebec and beyond, and possibly the Cowansville overthrust of Missisquoi and Brome counties, Quebec, though the age of the last has not been closely determined as yet. In any case the measured horizontal displacement of the last is 11 miles, and it is thought likely that the actual displacement is much greater. It is a nearly horizontal overthrust, whose plane is very close to the present surface, and along which the Georgian slates on the east have been shoved over the Trenton slates and limestones of the Farnham series to the west.

"The Rocky Mountains of Montana and Alberta are bordered on their eastern front, throughout at least 350 miles of their extent by great overthrusts whose planes dip in under the mountains at low angles. McConnell has estimated that on the south fork of the Short River in Alberta the horizontal displacement of the Cambrian strata---which here rest upon the Cretaceous---has been about 7 miles, while the vertical displacement amounts to approximately 15,000 feet.

"In the Glacier National Park of Montana, Willis found the Proterozoic strata which make up the outermost range (here called the Lewis Range) overthrust at least 7 miles upon the Cretaceous of the foothills. The dip of the thrust plane, as determined by Willis by graphic construction, ranges from 3° to 7° 45'. More recently Campbell has been able to show that where the Great Northern Railroad crosses the range this great mass of strata has been shoved at least 15 miles northeastward along the Lewis thrust plane, and were the original position of the mountain mass known the distance might prove to be much greater.

"At the International Boundary the northward continuation of the Lewis thrust has been termed the Waterton Lake thrust by Daly. The known extent of the bodily movement here represented is about 8 miles, as measured on the perpendicular to the line tangent to Chief Mountain and the outermost mountains of the Clarke Range. But the actual movement, according to Daly, has probably been 10 miles or more, and may be as much as 40 miles, for 'it is not impossible that the entire Clarke Range (the equivalent of the Livingston Range of Willis) in this region represents a gigantic block loosened from its ancient foundations, like the Mount Wilson or Chief Mountain massifs, and bodily forced over the Cretaceous or Carboniferous formations.'

"The Willard thrust discovered by Blackwelder in the Wasatch Mountains of Utah has a displacement, so far as exposed, of about 4 miles, though this is probably but a small fraction of its total displacement. Though the fault plane locally has a dip as high as 50° owing to later warping, it averages about 15°.

"The Bannock overthrust, recently described by Richards and Mansfield, when traced through southeastern Idaho and Utah along its course, now made sinuous by erosion, has a length of approximately 270 miles, and involves a horizontal displacement of not less than 12 miles. The thrust plane itself is a gently undulating surface nowhere steeply inclined, sometimes dipping to the east and sometimes to the west. If this slight plication be the result of subsequent folding, the shear plane must originally have been very nearly horizontal.

"In eastern Wyoming the Absaroka and Darby faults are really of the overthrust variety, although what remains of these planes shows a higher angle of inclination than most of the preceding. The fault plane of the Darby thrust is, in general, not far from parallel to the bedding of the overthrust sheet. East of Yellowstone National Park the Hart (sic) Mountain overthrust is thought by Dake to show a displacement of not less than 22 miles, making no allowance for recession of the eastern front by erosion. Assuming average thickness for the beds involved, the vertical displacement is over 6,000 feet.

"In the Alps, so long and carefully studied, some of the most remarkable structures known to geologists are still in process of being worked out. As yet there is lack of perfect accord as to some of the features of their interpretation. They have commonly been interpreted as extraordinary and wonderfully drawn-out overfolds (nappes de recouvrement). Among certain geologists there has developed a disposition to substitute, in interpretation, overthrust sheets of the Scottish Highland type for these extreme overfolds. If this be the true explanation, it would add to our list this remarkable structure of the Alps as a most pronounced and complicated case of low-angle faulting.

"Similar structures have been reported from Spain, Euboca, the Balkans, and the island of Timor; in the last case an extensive sheet of shallow water strata, ranging in age from Triassic to Eocene, has been thrust over what appear to be deep-sea deposits of nearly the same age." (R3)

The mechanical paradox. The 1918 date of the preceding survey of low-angle thrust faults assures us that it is incomplete. Even so, it does mention the five examples we will single out for detailed examination in X1-X5 below.

The reader will doubtless remark that nowhere in the above quotation has the "biological" solution to the phenomenon of inverted strata been mentioned. Only in the creationist literature will we find it asserted that inverted strata challenge the theory of evolution! However, this insistence upon a "geological" solution; i.e., thrust faulting; leads to a different kind of problem: the "mechanical paradox". This paradox is obviously deemed more palatable than toying with the theory of evolution.

For a definition of the "mechanical paradox" we rely upon R.A. Price's 1988 paper.

"Large overthrust faults are an intuitively implausible concept when viewed from the perspective of human experience with the mechanical behavior of rocks. Almost everyone has had some experience with the frictional resistance that must be overcome in sliding large blocks of rock at the Earth's surface. Thus, it is not surprising that at the beginning of the twentieth century, after most of the initial skepticism about the very existence of large overthrusts had been dispelled by the overwhelming weight of unequivocal geologic field evidence, the intuitively vexing question of the mechanical basis of large overthrust faults emerged as one of the most perplexing enigmas in geology. The problem was outlined succinctly in 1909 by Smoluchowski, and subsequent thinking about the matter has been constrained by his conceptual model of the mechanics of large overthrust faults.

> 'It is easy enough to calculate the force required to put a block of stone into sliding motion on a plane bed, even if its length and breadth be 100 miles...Let us indicate the length, breadth, and height of the block by **a**, **b**, **c**, its weight per unit volume by **w**, the coefficient of sliding friction by **e**; then, according to well known physical laws, a force **abcwe** will be necessary to overcome the friction and to put the block into motion. Now, the pressure exerted by this force would be distributed over the cross-section **ac**; hence the pressure on unit area will be equal to the weight of a column of height **be**. Putting **b** = 100 miles, we get a height of 15 miles, while the breaking stress of granite corresponds to a height of only about 2 miles. Thus we may press the block with whatever force we like; we may eventually crush it, but we cannot succeed in moving it.'

"With this statement, Smoluchowski had enunciated the mechanical paradox of large overthrusts---that the maximum possible width of an overthrust mass, as calculated in terms of the limiting condition for static frictional equilibrium of a rigid rectangular block on a horizontal plane surface, is substantially less than the widths of many actual overthrust masses, as determined on the basis of field relationships." (R56)

Factors enhancing the mechanical paradox. In selecting specific examples of overthrusts, we wish to challenge the geological explanation of the inverted-strata phenomenon as severely as possible. The parameters we must look for are:

(1) Fault planes that show little evidence that one set of strata was pushed over another; i.e., no slickensides, crushing, etc.
(2) Overthrust older strata that have ridden over younger strata for great distances and over huge areas.
(3) Overriding strata that are formed of incompetent rock; that is, easily crushed rock.
(4) Overthrust strata that have no "roots"; i.e., they are not related to nearby strata.
(5) Overriding strata of great thickness, such that the force required to overcome friction would be immense.

After describing in more detail the five examples selected (X1-X5), we will inquire into the various theories that have evolved to resolve the mechanical paradox and thus support the geological solution to the inverted-strata phenomenon. (X6)

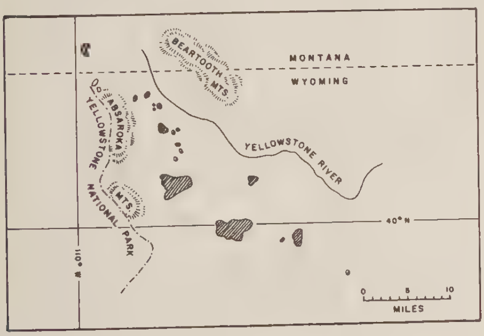
If the mechanical paradox cannot be resolved reasonably, the anomaly here is strengthened. Such an eventuality would make a biological solution look better, but philosophical factors will dominate this controversy for many years to come. (WRC)

X1. The Heart Mountain faults. Our first example turns out to be atypical of the genre. In fact, the Heart Mountain phenomenon is no longer considered an overthrust fault by most geologists; rather, it seems to be a complex and enigmatic combination of several types of faults.

The geological situation is as follows: In northwestern Wyoming, along the eastern edge of Yellowstone National Park, one finds large blocks of sedimentary rocks, Heart Mountain being one, that are composed of older rocks (Mississippian to Ordovician) resting upon a former land surface made up of younger rocks (Paleozoic to Tertiary). Superficially, one would think that Heart Mountain and the accompanying blocks would fit the overthrust definition perfectly, with post-faulting erosion having eradicated the rest of the once-continuous thrust sheet. In fact, W.G. Pierce, who has studied the Heart Mountain phenomenon for several decades, originally thought it was just that. His initial views---and a good description of the basic geology---are found in the following abstract of his 1957 paper.

"Abstract. In broad outline the Heart Mountain fault of Wyoming is a nearly horizontal thrust whose overriding sheet was derived from a source without any known roots, and whose frontal part has ridden across a former land surface. The suggestion is made here that this thrust and the near-by South Fork thrust are detachment thrusts or decollements, that is, they are sheets of sedimentary rocks which have broken loose along a basal shearing plane, have moved long distances probably by gravitational gliding, and have been deformed independently from the rocks below the fault plane.

"The present remnants of the Heart Mountain thrust sheet include more than 50 separate blocks which range in size from a few hundred feet to 5 miles across and which are scattered over a triangular area 30 miles wide and 60 miles long. The rock formations represented in the thrust blocks comprise a very limited stratigraphic range, none being older than the Bighorn dolomite (Ordovician) and none younger than the Madison limestone (Mississippian). The maximum stratigraphic thickness of the formations involved is 1,800 feet, but these include the most competent group of beds in the sedimentary sequence in this area.



Chunks of older rock (shaded) overlie younger rock at Heart Mountain. (X1)

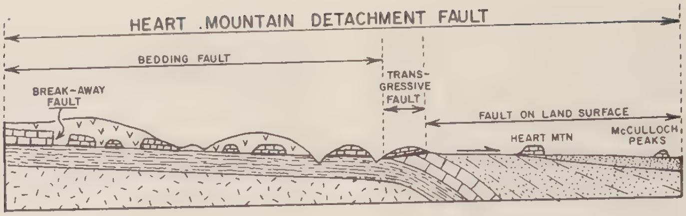
"In the northwestern part of its known extent the Heart Mountain thrust plane follows the bedding of the rocks and lies at the base of the massive and resistant Bighorn dolomite and above the underlying Grove Creek formation (a thin unit at the top of the Cambrian sequence). Near the center of the area here described this bedding thrust plane changes abruptly to a shear plane that cuts stratigraphically upward across the Bighorn and younger formations; the thrust plane then passes south-eastward onto and across a former land surface. The present thrust remnants on this surface are separated blocks that rest on rocks ranging in age from Paleozoic to Tertiary.

"In the area of the bedding thrust the displaced sheet was broken into numerous blocks which became detached from one another by movement, with large spaces or gaps separating them. Thus by tectonic denudation the thrust plane was exposed at the surface. Associated with the events accompanying the thrusting was the rapid formation of a stream channel deposit, here named the Crandall conglomerate. Next there followed the deposition of the 'early basic breccia.' This blanket is volcanic rock, which is now in the process of being eroded, has preserved much of the geologic record pertaining to the development of the Heart Mountain thrust since middle Eocene time.

"The concept is here advanced that, near the close of early Eocene time, the Heart Mountain thrust originated as a detachment or shearing off of strata at the base of the Bighorn dolomite. Near Dead Indian Hill the advancing southwestern edge of this bedding thrust sheet passed upward into a shear thrust and thence southeastward onto and across the land surface as an erosion thrust." (R18)

Above, Pierce has employed the term "tectonic denudation" to account for the great spaces separating the blocks of older strata found resting far out the younger strata. He uses this in preference to "tectonic erosion", which might imply erosion by water. Actually, there is no evidence at all for fluvial erosion, yet something has separated the blocks and exposed what seems to be a thrust plane. In employing "tectonic denudation", Pierce assumes that tectonic forces somehow separated the blocks, as now described.

The modern picture of the Heart Mountain phenomenon is seen in the accompanying geological cross section. It invokes a scenario involving several faults. Originally, the blocks of sedimentary rocks now found scattered for miles across northwestern Wyoming were contiguous, as shown in the drawing. "Something" then happened that broke



The Heart Mountain detachment fault, showing the detached pieces in cross section. (X1)

up the continuous strata and conveyed the pieces out over the younger rocks. This "something" was not a slowly encroaching overthrust. Instead, it is believed to have been something more violent, such as an earthquake (R54), a volcanic explosion (R25, R26, R28), or even a meteor strike (R11). Now, the phenomenon is more like a giant avalanche (ESM8) or megabreccia (ESD8), with mountain-sized units of sedimentary rocks rattling or "somehow" propelled away from their place of origin.

In summary, the Heart Mountain phenomenon, universally designated as an overthrust prior to the 1960s, is today regarded as more like a colossal debris slide (ESM8). The initial event stimulating the sliding is, however, a matter of conjecture; and the question of how blocks of rock miles in extent and some 1,800 feet thick can be propelled along a rough surface for scores of miles is still unanswered.

The latter question, however, is one that recurs with the bona fide overthrusts. In the Heart Mountain case, several mechanisms providing buoyancy and lubrication were considered: water pressure in rock pores, pressurized volcanic gases (R25), and acoustic waves (R43). No consensus exists here either.

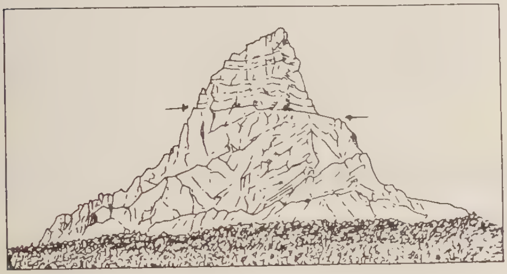
It does appear, though, that most of the problems of great overthrusts, so carefully introduced in X0, have been evaded at Heart Mountain by deciding that no overthrust exists. (WRC)

X2. The Lewis Overthrust and Chief Mountain. Like the Heart Mountain phenomenon, the Lewis Overthrust is found in a spectacularly beautiful part of North America. It runs for some 200 kilometers (estimates vary) along the eastern edge of Glacier National Park, Montana, and far into Canada. To the west are the Rockies; to the east, the High Plains. On the eastern fringe of the Rockies, geologists find a wide band of older rocks resting upon younger rocks, with huge outlier blocks, such as Chief Mountain (a tourist attraction), separated from the main sheet of older rocks. Superficially, Chief Mountain resembles Heart Mountain, being an isolated mass of older strata perched on younger strata. But the mainstream explanation is different here. The Lewis Overthrust is considered a classical low-angle thrust fault. And it is a big one---some 55-65 kilometers wide today. It probably extended much farther east, but erosion removed this portion, except for Chief Mountain and other outliers (often called "klippen"). Here in Montana and Alberta, if anywhere, we can compare the geological and biological solutions to the inverted-strata phenomenon.

A.N. Strahler has provided an excellent description of the mainstream scenario for the formation of the Lewis Overthrust.

"The Lewis Overthrust is exposed for some 200 km along the eastern front of the northern Rocky Mountains from northern Montana into Alberta. Here, thick, massive Precambrian sedimentary formations form the bulk of the mountain mass. Known as the Belt Series, its formations total from 3 to 7 km in thickness. Prominent as cliff makers in the area of the Lewis Overthrust are two great limestone formations, the lower one about 600 m thick; the upper one twice that thickness. Also present are quartzite and shale beds. A particularly noteworthy feature of the massive limestones is the presence in abundance of reeflike bodies of algal stromatolites, to which we shall make reference later. During the Laramide Orogeny that closed the Cretaceous Period, collision impacts from the west caused the Precambrian strata, which may have been little deformed up to that time, to be folded and thrust eastward over Cretaceous strata." (R54)

On p. 82, find the figure Strahler used in his discussion. In this illustration, we see how the postulated tectonic forces created a recumbent fold that broke along a low-angle thrust fault and carried the Precambrian Belt Series strata out over Cretaceous formations to the east. Erosion later removed much of the overthrust Precambrian strata on the far eastern edge. The sketch does not record the spectacular outliers left by the erosion, such as Chief Mountain and, in Canada, Crowsnest Mountain. To remedy this, we add a drawing of Chief Mountain, as it sits perched on the younger formations.



The upper section of Chief Mountain (marked by arrows) in Glacier National Park is solid limestone; the lower part is also limestone, but is broken by many oblique faults. The Lewis Overthrust is under the base of the mountain and marks the transition to much younger shales. (Geological Society of America, Bulletin, 13:307, 1902, X2)

At Chief Mountain, the conflict between mainstream geology and creationist geology comes into sharp focus. It is only fair to quote here a creationist's (C.L. Burdick's) view of the geology of Chief Mountain, which of course favors a biological, rather than geological, solution to the problem of inverted strata. Chief Mountain, in fact, has long been a key weapon in the creationists' attack on the theory of evolution.

"Chief Mountain. This is perhaps the most famous exposure of the Lewis Overthrust block, pictures of which have appeared in numerous texts on geology. It is a striking, majestic block of rock, standing alone, about 9,000 feet in height. Geologically it is considered an outlier or 'klippe,' or erosional remnant of the much larger Lewis thrust sheet, a mountain without roots, because Precambrian Altyn limestone and quartzite lie, apparently conformably, on top of Cretaceous dark shale. Much of the contact line is obliterated by talus, but where visible, it appears to be an erosional contact, without physical evidence of differential movement, such as gouge, mylonite, tectonic breccia or slickensides.

"This prominent light-colored cliff lies a few miles south of the international boundary with Canada. The best approach to the mountain is by a road along Kennedy Creek, from where a steep climb awaits the prospector.

"About two-thirds of the way up the mountain a sharp line of demarcation appears, which one at first glance might mistake for the thrust plane. On top of this plane are flat-lying Altyn Belt series limestones. Below the contact are quartzites and deformed Altyn limestones. The quartzites denote metamorphism-movement under confining pressure; followed by erosion, and truncation of the rocks. The flat-lying Altyn beds were laid down on top of them.

"Like Marias pass, the main tectonic activity shows up, not between the Precambrian Altyn and the Cretaceous

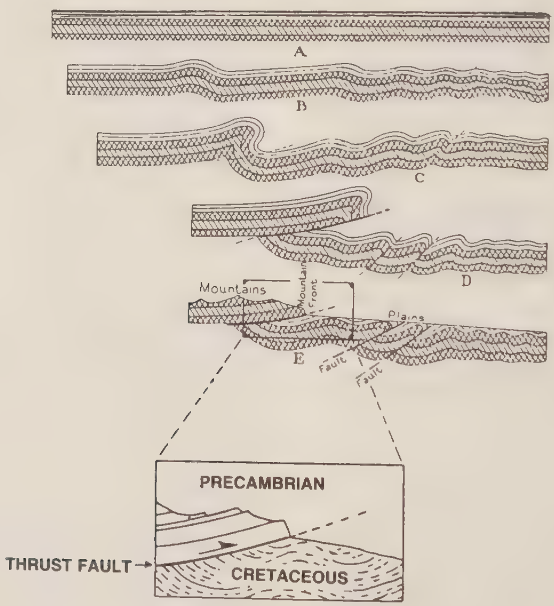
Crowsnest Mountain, Canada; another example of old-on-young rock in the Lewis Overthrust area. (X2) shale, where the thrust plane is supposed to exist, but within members of Altyn Formation itself. These evidences do not support the thrust-fault theory." (R24)

Needless to say, Burdick's interpretation of the contact zone at Chief Mountain, where Precambrian rocks rest on Cretaceous rocks, is not endorsed by most geologists. While the true contact may be sharp and seem conformable in some places, there is ample other evidence that tectonic forces caused considerable deformation along the fault plane. In this context, we quote C.P. Ross and R. Rezak.

"The fracturing that gave rise to the Lewis overthrust began several miles below the surface and probably a long way west of the site of Glacier National Park, where the hard but brittle rocks broke. A slab of tremendous dimensions began to move towards the plains region. As the process went on, the slab extended far northwestward into Canada in one direction and southeastward into southern Montana in the other, a distance of at least 350 miles. The fault surface beneath the displaced slab of rock sloped southwestward. Once the fracture had occurred the pressure that had caused it forced the displaced slab to travel eastward. In some places only a single fault surface formed, with crushed and crumpled soft rocks beneath it. Such a place appears in the cliffs north of Marias Pass...More commonly, numerous faults formed, the larger of which were roughly parallel to each other.

"Rocks between these faults were crumpled and crushed in a variety of ways. In some places the zone in which fracturing occurred was as much as 2,000 feet thick; generally it must have been at least several hundred feet thick." (R22) Not only is there ample proof of powerful tectonic forces, but the signs of faulting may occur far from the primary fault plane. (WRC)

In reality, the evidence for motion along the fault plane between old and young



Simplified cross sections showing folding and overthrusting thought to be responsible for the Lewis Overthrust, Glacier National Park. (National Park Service 1937 booklet, X2) strata is not particularly meaningful in trying to decide between the geological and biological solutions to the inverted-strata phenomenon. Whenever one finds slickensides, rock powder, and other signs of forces along a controversial fault plane, the creationist can always say that the differential movement was only a few feet rather than many miles. Even small faults generate ample signs of relative movement. If the Lewis Overthrust did move only a few feet, or few hundred feet, we would not have a geological solution to the inverted strata, despite the evidence for motion. Of course, mainstream geologists prefer to interpret the signs of motion along the thrust plane of the Lewis Overthrust as evidence of much greater movement. We seem to have a logical impasse here!

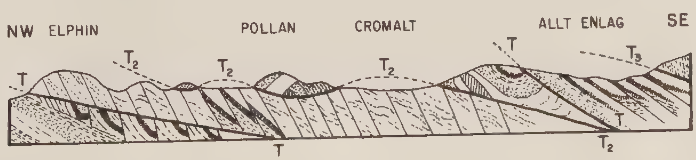
More telling in this whole business of interpreting inverted strata is the "mechanical paradox" introduced in X0. If geologists cannot produce a convincing resolution of this paradox, the biological solution, with its anti-evolution overtones, will remain a viable alternative, despite its unpalatability to the majority of scientists. As we shall see in X6, geologists have been finding more convincing ways of conveying huge slabs of strata over long distances. (WRC)

X3. <u>The Moine overthrust in the Scottish Highlands</u>. Almost a century before the American controversies over Heart Mountain and the Lewis overthrust, European geologists were debating the origin of inverted strata discovered in the Alps and the Scottish Highlands. In fact, the basic concept of the giant thrust fault, with great sheets of rock sliding for miles over adjacent strata, was really born in the Alps. (See X4.) Even so, when similar inversions of strata were found in Scotland, the application of the new theory was long delayed by R.I. Murchison, who strongly defended the Law of Superposition---at least in Scotland. The story of the Moine overthrust is worth summarizing because it demonstrates how one respected scientist, with a simple, attractive theory, can impede the development of science.

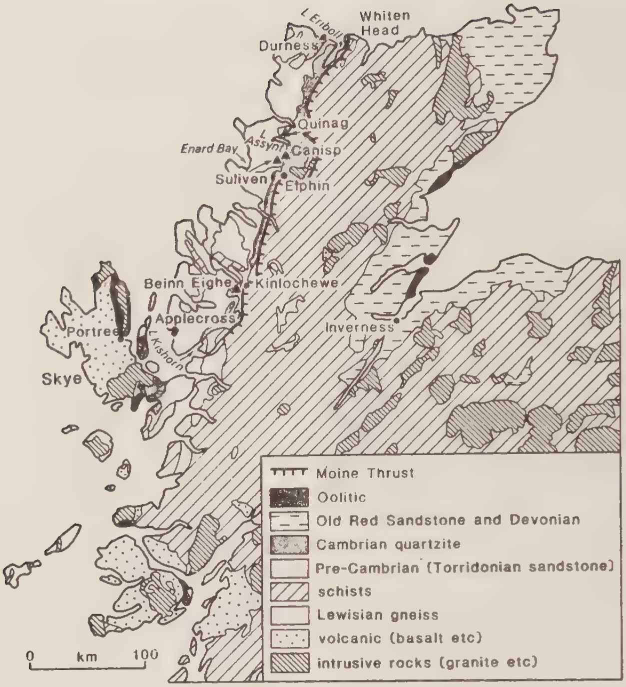
It should be emphasized in the beginning that the geology of the northwest Scottish Highlands is extremely complex, as illustrated by the many faults (Ts) marked on the accompanying cross section. The geographical scope is large, too, for the Moine overthrust, as conceived today, runs for almost 200 miles, with the thrust itself exceeding 10 miles.

For the debate over the Moine thrust, we quote J.W. Gregory.

"The geological interest of the area dates from the announcement by Macculloch, in 1819, of his discovery of fossiliferous rocks lying above gneisses, and covered by the gneisses and schists that form the great bulk of the Scottish Highlands. Murchison, with his keen scent for a good clue, visited the area, and he re-examined it after the discovery by C. Peach, in 1854, of the better fossils (now known to be Cambrian) in the Durness limestones. Murchison was convinced that the fossiliferous rocks were covered by the eastern gneisses, and, in accordance with the law of superposition, accepted the eastern gneisses as younger than the rocks beneath them. He regarded the fossils as Lower Silurian, and therefore did not shrink from the apparently inevitable corollary that most of the crystalline rocks of the Scottish Highlands are post-Lower Silurian in age. This conclusion had a worldwide influence. Similar crystalline schists form vast regions in all the continents, and they were at first regarded as all pre-Palaeozoic; but if the Scottish schists are altered Palaeozoic sediments, then the similar rocks elsewhere may include rocks of any geological age. To this day [1908] vast regions of schists and gneisses are mapped as altered Silurian, in



The Scottish Highland type of overthrust. Section width is about 6 miles. (X3)



A geological map of northwestern Scotland, where the Moine Thrust pushed older rock over younger rock over a wide region. (X3)

consequence of Murchison's work on the northwest Highlands.

"Murchison's views were at once opposed. The common-sense judgment of James Nicol showed him the improbability of Murchison's conclusions, and his keen and careful field-work revealed that the superimposing of schists over sediments was not an original arrangement, but was due to subsequent earth movements. The first controversy was short. Nicol's interpretation of the evidence had not the fascinating simplicity of the other theory, and it was not wholly right. The eastern and western gneisses are not simple repetitions of the same series, and Murchison was apparently right in his view that the upper gneisses and schists are an independent and younger series than the Lewisian gneisses, which underlie the Cambrian band to the west. Moreover, Nicol failed to realise that the apparent bedding planes in the eastern gneisses were not original, but secondary structures due to earth movements.

"Murchison, with a theory attractive by its charming simplicity and far-reaching results, and right in his recognition of the essential differences between the eastern and western gneisses, swept his critic from the field. Nicol, disheartened by the fate of views which he knew to be essentially correct, practically gave up geological reserach, and went to his grave, his geology despised and his conclusions rejected---by all except his wife." (R2)

Ironically, Murchison had quickly accepted the reality of thrust-faulting in the Alps but could not countenance it in Scotland! As we shall see, all was not clearcut along the contact zone. Back to the history, we skip the mid-1800s and focus on 1883, when A. Geikie, who had suceeded Murchison as Director of the Geological Survey, sent two of his best men to Scotland to try and resolve the dispute. J.W. Gregory continues.

"In 1883 Sir Archibald Geikie arranged for the detailed mapping of the Loch Eriboll district by the Geological Survey. The work was soon found to be far more complex than had been expected; it was attacked with invincible patience and thoroughness by the surveyors under Peach and Horne; the essential conclusions of Nicol and Lapworth were confirmed, and it was promptly announced in Nature that the Murchisonian theory must be abandoned." (R2) In sum, the existence of a giant overthrust was established to the satisfaction of mainstream scientists.

It was not difficult for Murchison to be misled in the region of the Moine overthrust. There is little direct evidence at the contact that rocks had slid over one another for many miles. To illustrate, S. Wintsch has written the following.

"Any field party working along the Moine Thrust will visit Knockan Cliff on the western edge of the Cromalt Hills. On the cliff face above the Nature Conservancy's information centre, Moine schists rest above pale limestones along an easily traced and remarkably smooth boundary. Peach and Horne marvelled at how much the contact, though born of earth movements on a 'stupendous scale', resembled that between two undisturbed rock formations." (R48)

And when Geikie was obliged to reject the theory of Murchison, he emphasized how conformable the rocks seemed along the thrust plane:

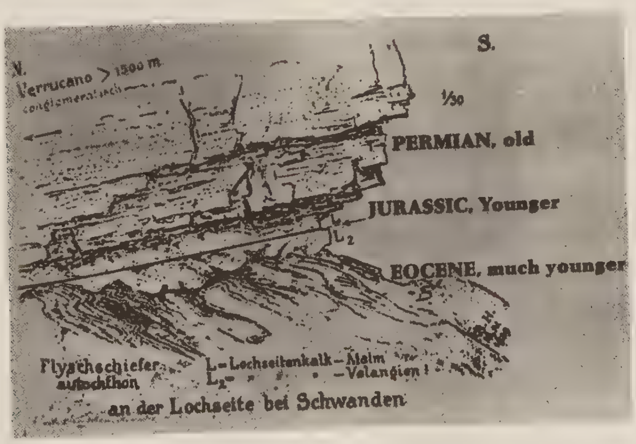
"Had these sections been planned for the purpose of deception, they could not have been more skilfully devised." (R48)

As in the case of the Lewis Overthrust, the Moine Overthrust does provide other indications of large-scale faulting, despite the "deceptive" contact zone. With all the signs of tectonic activity and metamorphism, the geological solution (overthrusts) definitely seems more reasonable than revamping the entire evolutionary sequence of life. (WRC)

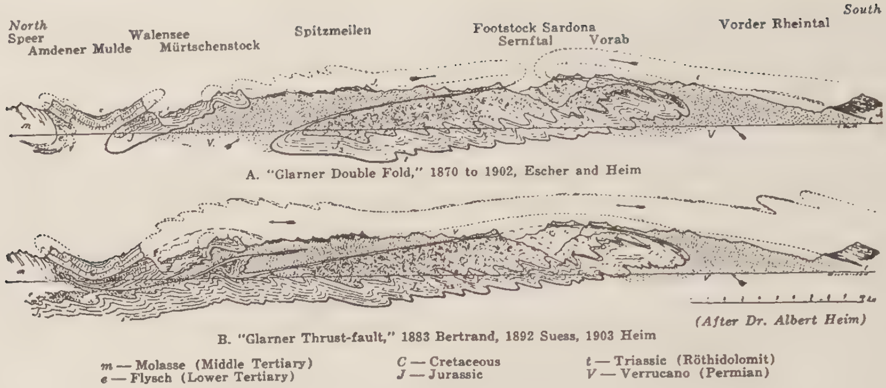
X4. The Alps. The geological situation in the Alps seems even more complicated than in the Scottish Highlands. Signs of folding and thrusting are everywhere. Inverted strata, too, are ubiquitous. The illustration shows a geological section at Glarus, Switzerland, home of the classical Glarus Overthrust. As with most of the overthrusts we have studied, the Glarus contact zone shows virtually no direct evidence of large-scale rock motion.

A. Heim, a noted Alpine geologist of the last century, described the geological situation in a 1907 lecture at Zurich.

"As in Glarus the valleys are cut down into the young Tertiary rocks, while the mountain peaks are crowned with the old Permo-Carboniferous (Sernifit). So also, for example, the Nikolai Valley is cut down through the Jurassic and the



A. Heim sketched this example of older-rock-on-younger rock at Glarus in the Alps. (X4)



The complex geology at Glarus variously explained. First, double, overturned folds were proposed; next geologists suggested a thrust fault without overturning. (X4)

Triassic, and the old crystalline schists form in the Matterhorn, Dent Blanche, and Weisshorn the overlying cover of a northerly directed overthrust fold. And in the very same manner the valleys of Schams and Rheinwald cut into Triassic schists, while the cliff-like tops round about are crowned with faulted caps of other older rocks of southern origin (for example, the limestone mountains of Spluegen). Thus we see that very many mountains of our Alps are composed, in their upper formations, of faulted older rocks which lie on top of younger ones without any direct connection with the bottom...These flat-lying faults, of which the Glarus folds were the first to be discovered, are a universal phenomenon in the Northern and the Central Alps, and their origins lie in the central and the southern regions." (R5)

The intent of the preceding quotation was to demonstrate how jumbled up the Alpine strata are. The geological solution to this most complex situation was to postulate thrust-faulting that generated huge recumbent folds (called knappes). Heim's conception of some of the thrust-produced knappes are illustrated in his sketches.

Admittedly, these huge overturned folds seem contrived, but to geologists (and scientists in general) the biological solution is unthinkable. This philosophical bias is abundantly clear in a quotation attributed to Heim:

> "The most incredible mechanical explanation is more probable than that the evolution of organic nature should have been inverted in one country as compared with another." (R5)

This is indeed a serious millstone to place about the neck of Science. (WRC)

X5. The Appalachian thrusts. In X1-X4, we have been properly impressed by the large-scale, low-angle thrust faulting observed at the Lewis Overthrust, in the Alps, and in the Scottish Highlands. We have seen thrusts of 20-30 miles, perhaps even more, claimed as explanations of the observed inverted strata. In the Appalachians, we meet---indirectly---thrusts with horizontal displacements of 10 times those seen at the "classical" overthrusts. We say "indirectly" because the extent and character of the greatest Appalachian thrusts have been determined primarily by seismic methods, for they are, for the most part, covered by thousands of feet of rock.

Overthrust faults in the southern Appalachians have long attracted the attentions of geologists, as in the 1891 survey by C.W. Hayes. (R1) In his long chapter on "upside-down strata", G.M. Price, in 1926, remarked on an Appalachian thrust fault running 375 miles through the mountains of eastern Tennessee and northern Georgia. In the Appalachians, Price said, older rocks overlap younger rocks by distances of as much as 11 miles. Such great horizontal displacements, he said, "have provoked the wonder of the most experienced geologists," (R5) Little did these earlier geologists know what lay farther down.

The true extent of Appalachian overthrusting was not appreciated until systematic seismic probing began in the late 1970s. (R36, R41) A group of earth scientists, under the aegis of COCORP (Consortium for Continental Reflection Profiling), began using explosives and "thumpers" to make seismic profiles across the Appalachians in several areas.

"The Cocorp profile showed that the Appalachians are the product of enormous lateral movements over the past half-billion years. These movements have thrust a sheet of relatively thin, crystalline rock at least 270 kilometers to the west and over a layer of younger sedimentary rock one to five kilometers thick. Like a great wedge, tapering from a thickness of 15 kilometers in the eastern Appalachians to 5 kilometers in the west, the overlying rock was thrust across a series of relatively shallow, easterly-dipping fault planes." (R47)

Thus, in the Appalachians, we see (or our instruments see) thrusts an order of magnitude greater than the surface manifestations evident in the Rockies, the Alps, and Scotland. Much work remains to be done in the Appalachians. For example, deep drilling will be required to confirm the seismic profiling.

In none of the recent papers we have collected on the Appalachian thrust faulting is the "biological solution" for the explanation of inverted strata even mentioned. Only the creationists consider this possibility. Instead, mainstream science now sees overthrusts as only one consequence of plate tectonics, with its colliding continental masses and migration of terranes from one part of the globe to another. (See ESR9.) What the discovery of great subterranean thrust sheets has done is to demote even further the "biological solution" and underscore the importance of resolving the "mechanical paradox" of low-angle, thin-sheet, long-distance thrust faulting. (WRC)

X6. Resolving the "mechanical paradox". As detailed in X0, the "mechanical paradox" relies upon a very simple model of thrust-block motion. The paradox arises because calculations show that a force applied to the strata will crush them before static friction can be overcome.

The simplest resolution of this paradox reduces the coefficient of friction along the thrust plane. Geologists gave a sigh of relief when, in 1959, M.K. Hubbert and W.W. Rubey showed that pore-water pressure in strata could act like a hydraulic jack and, in effect, "float" one stratum on another! This would, of course, greatly reduce the coefficient of friction, and strata could slide over one another before being crushed by tectonic forces. (R19)

Even though the Hubbert-Rubey hypothesis is still widely acclaimed in the textbooks as solving the thrust-fault problem, serious objections arose. The essence of the criticism is that it is impossible to imagine conditions where pore-water pressures could be trapped in the rocks along the thrust plane. (R22, R54)

One should not let imagination rule, however, because in 1981 the drilling ship Glomar Challenger discovered that extremely high pore-water pressures can and do exist in deep-sea strata. Drilling in the western North Atlantic, Glomar Challenger scientists found Lower Miocene sediments overlying younger Pliocene sediments. Further, they were able to measure water pressure within the formations as 20 bars above the hydrostatic pressure of 550 bars. These measurements supported the Hubbert-Rubey model---at least in the deep ocean. (R44)

A more recent approach to resolving the mechanical paradox denies a basic assumption made in previous models. In 1988, R.A. Price pointed out that these models visualize that motion along the thrust plane occurs everywhere simultaneously. Real thrusts do not behave in this way. Instead, Price stated:

> "The shape and size of overthrust faults result from the propagation of dislocations, and this process is controlled by the strength heterogeneity and anisotropy of the rock mass as well as by variations in the regional stress field, but not by the frictional resistance to sliding integrated over the entire fault surface." (R56)

To summarize the theoretical situation, we can say that the Hubbert-Rubey pore-water-pressure model may not work in all instances, due to the impossibility of maintaining sufficiently high pressures along the whole thrust plane. It may well work in oceanic sediments, however. The dislocation model of Price shows great promise, but it is so recent that professional critiques are not yet available.

Has the mechanical paradox been resolved? The two models described above go a long way in this direction. In fact, they go so far that the inverted strata, by which overthrusts are usually detected, seem well within the reach of a "geological solution"; and that the unthinkable "biological solution" will not be required. (WRC)

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ESR4 Near-Global Unconformities

Description. Unconformities (usually erosional) that prevail over most of the globe.

Data Evaluation. The nature of the great Cambrian-Precambrian unconformity has received a modest amount of attention in the geological literature. Little has been found so far on other worldwide unconformities. Rating: 2.

Anomaly Evaluation. Unconformities in themselves are scarcely anomalous; indeed, they are both common and generally well-understood. But when an unconformity is synchronous worldwide, geologists must invoke a global mechanism of some sort. Therefore, the anomalousness of a global unconformity resides in the force that produced it. Foremost on the list of potential mechanisms capable of causing global unconformities are: (1) tidal forces created by the close approach of the moon in the distant past; (2) great tsunamis raised by the impacts of large meteors at sea; (3) global ice ages; and (4) large fluctuations in sealevel. The latter two mechanisms, of course, need elaboration as to their driving forces. The first two in the list are definitely catastrophic in nature, although they are no longer rejected out-of-hand by today's geologists. In summary, one can say that global unconformities and their implied mechanisms challenge no vital geological paradigms. Even so, towering lunar tides and meteor-generated tsunamis, if they actually occurred, do require significant reworking of the earth's history. Rating: 2.

Possible Explanations. See above.

Similar and Related Phenomena. Chemical anomalies in the Stratigraphic Record (ESC1); deposits covering unusually large areas (ESD9); raised beaches and terraces (ETE).

Examples

X1. The Cambrian-Precambrian Unconformity. A profound unconformity separates the Cambrian and Precambrian periods. To many geologists, this unconformity is clear-cut and serves as evidence of a catastrophic global event of some sort; others are unsure about the nature and significance of this mysterious episode in our planet's history.

The event usually invoked to account for the purported unconformity is the close approach of the moon, some 700 million years ago, which raised colossal tides that deeply scoured the earth's crust. W.S. Olson, who favors this scenario, has provided us with a good introduction to the phenomenon.

"An examination of the geologic record discloses a set of phenomena which may be explained by such abnormal lunar tides. The tidal theory in fact seems to give a more logical, comprehensive explanation than the currently accepted theory which postulates a period of world-wide glaciation as the cause. The glacial theory has been questioned by some competent geologists on entirely different grounds even though no satisfactory alternative has been provided. A critical examination of the facts is surely justified. This should be of a scope much broader than can be attempted in these few pages, which are merely intended to outline the problem.

"The phenomena in question are those related to the Cambrian-Precambrian unconformity. This is the most striking and universal break in the succession of rocks covering the earth. The event which they represent has been used to divide the history of our planet into two unequal and contrasting parts. The continental nuclei at that time were largely stripped down to the crystalline basement. Ancient mountain systems were worn down to their roots, reducing the continents more nearly to a plain than they ever have been before or since, leaving a clean slate on which the record came to be written which is usually called historical geology.

"The period of world-wide erosion immediately preceding the Cambrian was called the Lipalian by Walcott (1910), who found it a cause of wonder and speculation to account for the great difference between the rich fauna in the Cambrian and its near absence in older formations. He looked in vain for marine deposits of this period which would contain the evidence of faunas ancestral to Paleozoic life. The deposits of this period are plentiful but enigmatic, and strangely barren in organic remains." (R2) For a fuller account of Olson's theory involving lunar tides, see ESD9-X5.

It may be mentioned in passing that the basal conglomerates and the unconformity thought to lie below them everywhere are considered by A.O. Kelly to be evidence for his scenario of massive marine incursions caused by meteor impacts at sea. (R1)

D.V. Ager's characterization of the Cambrian-Precambrian juncture. Ager has been much more cautious about this supposed unconformity, preferring to empasize the basal conglomerates that are ubiquitous at this point in time.

"Even more remarkable than the basal Ordovician quartzite is the one that is found, almost all over the world, at the bottom of the Cambrian. Here dating becomes more and more problematical as the time spans become longer and longer. One is tempted to get mixed up with arguments about the origins of life and the beginning of the main fossil record, of the mysterious 'Lipalian Interval' that was once favoured and of great world-wide marine transgressions. Perhaps all that is safe to say in this context is that very commonly around the world one finds an unfossiliferous quartzite conformably below fossiliferous Lower Cambrian and unconformably above a great variety of Precambrian rocks. This is true wherever one sees the base of the Cambrian in Britain, it is true in east Greenland, it is true in the Canadian Rockies and it is true in South Australia. In fact it is even more remarkable than this, in that it is not only the quartzite, but the whole deepening succession that tends to turn up almost everywhere; i.e. a basal conglomerate, followed by the orthoquartzite, followed by glauconitic sandstones, followed by marine shales and thin limestones." (R4)

A fuzzier portrait of the unconformity. The situation at the Cambrian-Precambrian boundary is even murkier to R.W. Morrell.

"The question of the boundary between the Cambrian and the Precambrian is of some interest; and has a direct bearing upon the claims made for some recent discoveries in Australia which have been placed in the late Precambrian. On an international basis, the boundary between the Precambrian and Cambrian is distinguished in terms of a discontinuity. Where found it is argued that the stratum above is Cambrian and that below Precambrian. This discontinuity is not present in Britain, and even where it is present in other countries (and it is not always easy to see, or see at all) the actual rocks can tell us nothing about the supposed age difference between the two systems. Thus it can be argued that if a discontinuity can be observed, it simply represents a violent upheaval of short duration, certainly not one of a duration long enough to account for evolutionary change. There is in fact considerable difficulty in determining what is and what is not Precambrian and Cambrian, for comparison of rock samples can demonstrate nothing positive other than their composition."

Morrell then quotes J. Challinor and F.H.T. Rhodes by way of support.

> '...when strata with a Lower Cambrian fauna are conformably underlain by a great thickness of unfossiliferous strata it must be somewhat uncertain whether these lower strata, particularly the lowest of them, should be classed as Cambrian or Precambrian.' (J. Challinor)

> 'The base of the Cambrian is not always a precise stratigraphic horizon. Stratigraphic correlation is almost always a matter of faith, done entirely on an intercontinental scale by matching similar faunas. In the case of the lowest Cambrian there is a distinct possibility that our correlation may be tenuous. This means, in short, that fossil material claimed as Precambrian could just as well be ascribed to the Cambrian, and thus the break in continuity becomes not simply a gap but a yawning chasm.' (F.H.T. Rhodes) (R5)

In summary, the Cambrian-Precambrian boundary is not really distinct enough to encourage any specific hypothesis, although the huge, widespread deposits of basal conglomerates certain hint strongly at some type of catastrophic event, (WRC)

X2. Synchronous, world-wide unconformities in the late Paleozoic. The only other examples of global unconformities found so far are very common in the Carboniferous and Permian periods. C.A. Ross and J.R.P. Ross have described these and have drawn a significant conclusion from them.

"Abstract. More than fifty transgressive-regressive depositional sequences are present in Carboniferous and Permian shallow marine successions on stable cratonic shelves worldwide. These were synchronous depositional events resulting from eustatic sea-level changes that generally ranged from 100 to 200m. Each transgressive-regressive sequence is correlatable using current fossil knowledge. They average about 2 m.y. and range from 1.2 to 4 m.y. in length.

"The presence within these strata of numerous, synchronous unconformities of considerable duration and worldwide extent suggests that the fossil record is very incomplete and that we are studying a punctuated fossil record and not a punctuated evolution based on a highly irregular mutation rate. These late Paleozoic transgressive-regressive depositional sequences facilitate correlations because depositional histories of a rock succession can support interpretations of faunal assemblages and faunal similarities in evaluating age relationships." (R6)

The Ross's claim that the fossil record is very incomplete is contrary to that stated by proponents of punctuated evolution. The character of the fossil record is treated in the series B (Biology) volumes in the Catalog of Anomalies. Further, the sequences described by the Ross's are fairly regular and might well be classified with the cyclothems in ESR5. (WRC)

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ESR5 Anomalies of Rhythmites and Cyclothems

Description. Features of rhythmites and cyclothems that are not well-explained by prevailing geological theories, such as:

1. Cyclicity that is uncorrelated with known natural cycles.
2. Apparent climatic changes, as recorded by rhythmites and cyclothems, that are correlated with astronomical phenomena (viz.,earth's orbital eccentricity) that theoretically have near-negligible effects upon the earth's insolation.
3. Cyclic geochemical phenomena (flint layers, banded iron) that are not well-understood.
4. The persistence of cyclothems and rhythmites, including extremely thin members, over such great areas that tectonic explanations seem compromised.
5. The incompatibility of some cyclothem members (fireclays) with geological dogmas (the in-situ theory of coal's formation).
6. Rhythmite counts and thickness measurements that lead to estimates of the durations of geological periods that are considerably shorter than those estimated by standard radiometric methods.

Data Evaluation. The literature on rhythmites and cyclothems is immense and largely the product of modern science. Our collection of references is representative only. Rating: 1.

Anomaly Evaluation. The above list of major anomalies that appear in this review of the rhythmite and cyclothem literature challenges several well-established geological hypotheses. In addition, there are some phenomena that remain unexplored and unexplained. It seems that the rhythmites and cyclothems are signals recorded in the Stratigraphic Record by forces we are only beginning to appreciate. Rating: 1.

Possible Explanations. The now-recognized, potential driving forces that modulate the Stratigraphic Record are described below in X0.

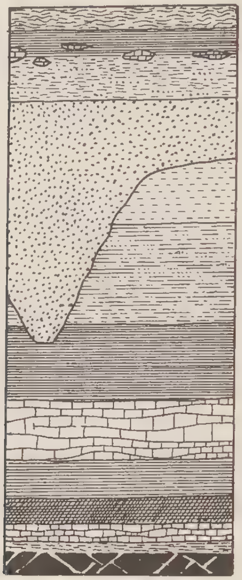
Similar and Related Phenomena. Coal anomalies (ESC14); radiometric dating discordances (ESP12); deposits of great areal extent (ESD9); periodicity of crater ages (ETC4).

Examples

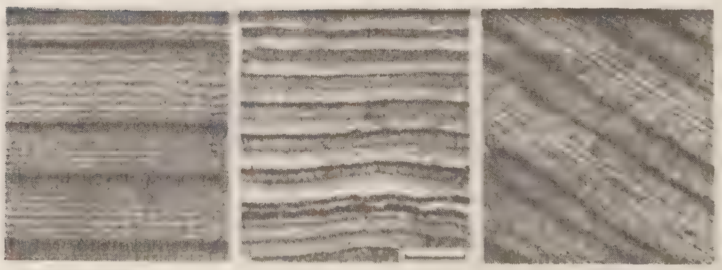
X0. Introduction. Even the casual observer of sedimentary rock formations recognizes their layered structures. Some sedimentary strata are immensely thick, measuring many thousands of feet without discernable breaks in deposition. Millions of years may have been required for their accumulation. On the other hand, some strata consist of delicate laminae only a millimeter or two in thickness. Hundreds of thousands of these laminae may be counted in a single formation. Such laminae appear to be the sedimentary manifestation of some cyclic phenomenon; perhaps as long as the annual change in the character of the sediment carried into a lake, or as short as the deposit from an afternoon thunderstorm. Most strata and laminae suggest no anomalies, but some may record astronomical, geological, and meteorlogical processes and events we do not fully understand.

If a lamina or layer represents an annual deposit, it is termed a "varve". However, it is sometimes difficult to prove that laminae are truly annual records. They may represent only a tidal cycle or perhaps something longer, say, a decade-long climate fluctuation. The word "rhythmite" is preferred here over "varve" because of this problem of identification.

A "cyclothem" typically consists of a regular sequence of strata, such as clay/coal/shale/limestone/sandstone/etc., that keeps repeating, sequence upon sequence. The individual layers in a cyclo-



An idealized Illinois cyclothem. All ten members are never present in the same place. In illinois, the most common sequence is: 1, and/or 2, 4, 5, 9, and 10. (X0, X7)



Thin sections of late Precambrian rhythmites. Viewed with transmitted light, the more opaque, clayey material is darker than the more translucent sandy layers. The scale bar in the center photo is 1 centimeter long and applies to all three sections. (X0) them may be measured in inches of thickness, or many feet; they may be continuous for hundreds of miles. In general, cyclothems are more massive than the rhythmites; but there is no "official" size criterion. The two terms are sometimes used interchangeably in this section.

Do rhythmites and cyclothems have different origins? The former are usually viewed as the consequence of short-term changes in the nature of the sediment being carried into a lake or estuary by water. In contrast, cyclothems are thought to be created by cyclic changes in the basin of deposition, such as wide-area subsidence or elevation. Climatic changes, too, may play a role in building cyclothems; but climate may control rhythmite formation also. Some extreme catastrophists even maintain that cyclothems are deposited quickly by massive floods or marine inundations.

In the rhythmites, the sharp-eyed geologist often sees "cycles within cycles". The thickness, chemical composition, organic content, grain coarseness, and other factors may seem to respond to tidal, sunspot, and earth-orbital factors. In fact, such orbital parameters as the earth's eccentricity, its tilt, and its distance from the sun are thought to modulate the layered structures.

From the viewpoint of the anomalist, the lack of consensus as to the origins of rhythmites and cyclothems provides much grist. But there may be deeper issues involved, as delineated above under Description.

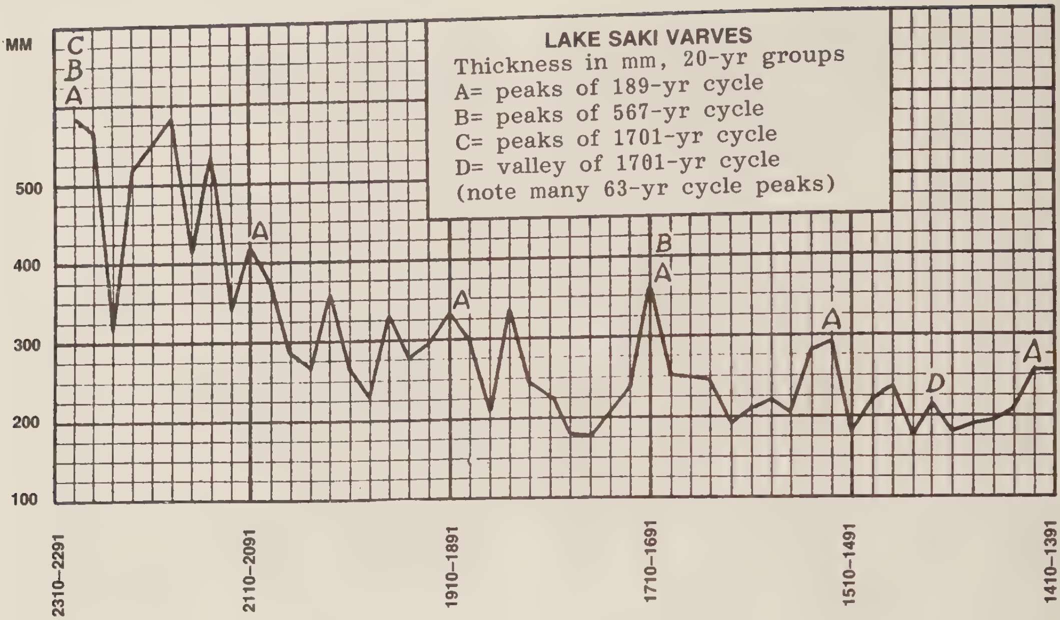
In the following sections, we will search out anomalies---sometimes in laborious detail---in the Stratigraphic Record, beginning with the Quaternary Period and working downward until we encounter the Precambrian. We shall find that, even a billion years ago, cyclic phenomena modulated much sedimentation.

X1. The Quaternary Period, Geologists divide the Quaternary into a Recent Epoch (0-10,000 years ago) and the Pleistocene Epoch (10,000 to about 1.6 million years ago). We will commence with studies of Recent rhythmic sediments and then move into Pleistocene time; but readers should recognize that some analyses overlap both epochs.

Sunspot-cycle signal in Alaskan lake varves. "A sequence of 236 varve thickness measurements by Perkins and Sims from proglacial Skilak Lake in southern Alaska is shown to contain spectral features similar to those of the sunspot index. In general, the varve spectrum qualitatively mimicks that of the sunspot index, with discrepancies perhaps arising from the misinterpretation of random summer layers as annual increments (varves). These discrepancies may be largely removed through maximization of the sunspot index-varve cross correlation whereby a time-scale factor increment is applied to the varve series measurements. Varve thickness is positively correlated with the sunspot index and with vanishing lag (insofar as can be resolved). As varve thickness and meteorological variables have previously been shown to be strongly correlated, a direct link between the sunspot index and varve thickness is suggested by way of climate response to solar variations." (R57) The link between the sunspot cycle and terrestrial weather is not well-established. Varve studies like this strengthen the link, although the real mechanism is unknown. (WRC)

A search for cycles in the sediments of a Russian lake. The dangers of varve analysis may be seen in a 1940 analysis of a large series of lake varves by a meteorologist. This type of research was suggested to H.P. Gillette by varve cycles observed in California rocks. We now quote a few paragraphs from one of his papers.

"This led to a search for a similar triple-progression series of cycle lengths in the varves measured by Schostakowitch in a core taken from the mud of Lake Saki, Crimea. He measured about 4200 varves, going back from the present to about 2300 B.C. By the method of simple averages I found them in cycles of 7, 21, 63 and 189 years very clearly shown, and good indication of two more cycles in this triple-progression series of 567 and 1701 years...The last maximum of the 1701-year cycle was 1116 A.D., the exact date of which is determinable by means of its short subcycles. The first peak of this grand cycle was 2286 B.C., at about the time the flood levels of the Nile, scribed by the Egyptians in the rocks, averaged some 23 ft. higher than in modern times! Fig. 2 shows this peak and that of seve-



Thickness of varves at Lake Saki by 20-year groups. Peaks of the 189-year cycle are marked A. (X1)

ral of the shorter subcycles, notably the 189-year cycle. The latter cycle is also to be seen in Nile flood levels and New England rainfall...The 189-year cycle had its last rainfall maximum in 1872 and its next minimum will be in 1966, which will be also a minimum of its 1701-year harmonic supercycle. It is probable that for many years before and after 1966, dry years will recur frequently, possibly producing in many regions a series of droughts more severe than any in historical times."

.....

"The great sunspot cycle and its affiliated weather cycle appears to be exactly 189/17, or about 11.118 years, and therefore a subcycle of the 189-year cycle. Its amplitude in varves, tree-rings and rainfall is far less than that of the 21-year cycle.

"These studies indicate that:

(1) Cycles occur in several triple progression series.

(2) All cycles are harmonic.

(3) Long compound cycles result from the combined effects of short cycles.

(4) These laws hold not only as to weather but as to sunspots, magnetism, oblateness of the earth, sea-levels, earthquakes and several other terrestrial phenomena. From this, and other evidence, it seems to follow that the cause of many kinds of terrestrial cycles is cyclic influx of solar electrons (negative charges), as outlined in my earlier papers." (R13) Today, few geophysicists make such broad claims for sunspot-cycle analysis. (WRC)

<u>A caveat from a Swiss Lake</u>. Some of the problems plaguing varve analysis are evident in a report by A. Lambert and K.J. Hsu.

"Dating of recent varve-like sediments from the perialpine Lake of Walenstadt (Walensee) indicates that the number of laminae deposited in the 165 years between 1811 and 1976 ranges from 300 to 360 depending on sample location. Direct evidence that up to five graded laminae may be deposited during one year was found in 1912 by an engineer of the Swiss Federal Hydrological Agency who was using sediment traps to determine the annual sedimentation rate. These layers are considered to be deposits of continuous-fed turbidity currents generated by hyperpyenal inflow during river-flood stages. Current measurements revealed that these underflows can occur sporadically throughout the year, but are especially common during the snow-melting season and after heavy rainfalls. ...The laminated sediments of the Walensee do not represent deposition of annual cycles and these non-annual varve-like sediments seem to be less regularly rhythmic than the annual varves of Lake Zurich." (R48)

Rhythmic deposits in icebergs. Icebergs often contain obvious stratification, usually due to dust and ash. Neatly striped icebergs have been observed around Antarctica, as in the following report from the R.R.S. John Biscoe, dated March 22, 1971, when in the South Orkneys.

"Some of the bergs were halved black/white with large areas of each, whereas others were composed of many alternating bands. One berg in particular, approx. 100 yd long, exhibited about 20 alternating bands spaced at fairly regular intervals. On some of the bergs the white ice was discoloured and appeared to be carrying a brown sediment, but this did not seem to be connected in any way with the black ice. All of the affected bergs were thought to be inclined at 90° to the position in which they were originally formed and the layers of ice were therefore vertical or near vertical." (R39) The nature and origin of the surprisingly regular black stripes are unknown.

Milankovitch cycles in the Phanerozoic. In the sedimentary deposits of the last 600 million years (the Phanerozoic), many students of cycles profess to see Milankovitch cycles, presumably caused by long-term variations in the earth's orbit. As in the case of the sunspot-cycle studies mentioned above, dangers lurk here. T.J. Algeo and B.H. Wilkinson showed in 1988 that many claims of Milankovitch signals in sediments are likely erroneous.

"Data on more than 200 mesoscale sedimentary cycles indicate that Phanerozoic cycle periods are randomly distributed with respect to the four major Milankovitch parameters, except Late Mississippian through Late Pennsylvanian cycles which show positive clustering about the 413,000 yr eccentricity period...Comparison of short-term Holocene sedimentation rates and long-term Phanerozoic accumulation rates for cyclic peritidal and deltaic facies suggests that average cycle deposition occurs in about 1/30 of the time represented by average cycle period. Thus, long, unconstrained intervals of non-deposition predominate in most cratonic and continent-margin cyclic sequences." (R75) See ESR1-X9 for a discussion of "missing" sediments and questions about the accuracy of the geological time scale.

Despite their generally negative article, Algeo and Wilkinson did see a Milankovitch-type, long-term eccentricity cycle in the Phanerozoic sedimentary record. Recent measurements of oxygen-isotope ratios in deep-sea sediments, which reflect the amount of glacial ice present in the world, are correlated with the main eccentricity cycles over the past 800,000 years. The puzzle here, if these correlations hold up, is that terrestrial insolation changes by only 0.1% due to changing orbital eccentricity. R.A. Kerr remarked: "One of the great mysteries has been how such large climatic changes [the Ice Ages] could be prompted by such small effects on insolation." (R54)

The shorter Milankovitch-type cycles, which are due to other orbital parameters (axial tilt, etc.), continue to be found in sedimentary deposits. For example A. Yamamoto et al have provided the following abstract.

"A time sequence of grain size distributions from the Pleistocene sediments in Lake Biwa, located in the central part of Japan (35° N, 136° E), has dominant periodicities of 41,000, 23,000, and 19,000 years, which are very close to those predicted from the astronomical theory of paleoclimate introduced by Milankovitch. The time variation of the grain size is very similar to that of insolation of caloric summer in the Northern Hemisphere." (R56)

Recent cyclothem-like structures. The deposits mentioned below do not cover the huge areas of the Carboniferous cyclothems. Still, it is interesting that the basic cyclothem patterns are being created today.

"Sub-surface sections in non-glacial deposits in the Po and Ganges deltas show successions said to be similar to cyclothems from the Pennsylvanian. Similar cycles are also known from other deltas, and from the coastal plain area of Texas. Holocene deposits in the Mississippi delta show a clear succession of transgressive marine deposits and pro-deltaic silts and clays beneath variable regressive sediments, the similarities between this sequence and many cyclothems of coal-bearing type being indeed striking." (R22) Since these cyclothem-like structures are very recent, it should be possible to determine exactly how cyclothems originate. (WRC)

X2. The Tertiary Period. Geologists divide the Tertiary into five epochs:

Pliocene (1.6 to 5 million years ago)
Miocene (5 to 24 million years ago)
Oligocene (24 to 37 million years ago)
Eocene (37 to 58 million years ago)
Paleocene (58 to 66 million years ago)
(R66)

The Green River Eocene rhythmites. The Green River Formation covers more than 20,000 square kilometers of Utah, Wyoming, and Colorado. M.D. Pickard and L.R. High, Jr., state that the deposit exceeds 2200 meters in thickness and spans 13 million years. (R33) On the other hand, A.N. Strahler puts the thickness at 600 meters and sets the time span at 5-8 million years. (R66) Both sets of figures are impressive when one discovers that this very thick formation is really one colossal sandwich of very thin, regular couplets---millions of them!

One couplet element is marlstone (a form of calcium carbonate); the other element is mainly sandstone and kerogen (a hydrocarbon mixture). The marlstone component is generally only about 0.2 millimeter thick. Although each couplet thickness is remarkably uniform over great areas, a superficial examination is sufficient to convince one that couplet thicknesses vary as one counts down (or up) the vast stack of laminae. Furthermore the thicknesses vary systematically. Here is a unique, multimillion-page record of "something".

There is no assurance that each couplet is a varve and represents a full year. W.H. Bradley, an early student of the Green River Formation, pointed out that the kerogen was not completely separated from the marlstone. And what sort of annual cycle would generate a marlstone/kerogen couplet?

Bradley ventured that the kerogen might be represent the lake's seasonal product of organic material, while the calcium carbonate might have been produced by planktonic algae. Both would have been synthesized mainly in the summer months, but because they would sink at different rates they would settle out as annual couplets. Using this reasoning, Bradley assumed the couplets were varves and began to decipher the cycles represented in the long record.

After many years of work, Bradley thought he had identified three cycles in couplet thickness. Their periods were: (1) a bit less than 12 years (the sunspot cycle); (2) 21,630 years (perhaps the earth's precession cycle); and (3) 50 years (uncorrelated with any recognized natural cycle). (R66)

Besides the major questions relating to the true nature of the couplets and the identities of the external forcing cycles, two other "problems" remain:

(1) How could such thin laminae maintain their thickness and integrity over thousands of square kilometers? One would naturally expect that earthquakes, storms, volcanic eruptions, and other phenomena would, over millions of years, have disturbed the long sequence of couplets. A radical answer might be that the couplets were the consequence of many short-term chemical reactions in the lake waters. The mainstream answer? Quiet prevailed during this long period.

(2) Unmentioned above are the abundant, near-perfect fish fossils embedded in the Green River Formation. If a dead fish sank to the lake's bottom, wouldn't it be consumed or decay long before it was covered by the very thin annual layers of kerogen and marlstone? Fossilization would only proceed after burial, according to current thinking. Most geologists would respond that the bottom of the lake was probably devoid of scavengers and decay-causing bacteria because of the lack of oxygen and presence of hydrogen sulphide and other chemicals. (R66)

According to A.G. Fischer, the Green River Formation also displays both the short (100,000-year) and long (400,000-year) cycles corresponding to the varying eccentricity of the earth's orbit.

Fischer also adds a pertinent generalization:

"Oscillatory patterns in stratigraphy show that orbital variations drove pre-Pleistocene climates in various ways. The record is best expressed in lacustrine sediments, which reflect variations in lake level, and in evaporite sediments, which reflect variations in salinity. These are essentially closed systems in which varving provides a time base. Low-latitude evaporites and midlatitude lakes have recorded precessional couplets bundled into sets corresponding to the short cycle of eccentricity as far back as Triassic and Permian time. They have not changed their absolute or relative length appreciably during this interval." (R62)

Fischer's implication is that the earth's orbit has been stable for roughly the last 200 million years. Therefore, orbit-altering astronomical catastrophism probably did not occur during this time span. However, we do find great terrestrial craters within this time frame. (See ETC3.) Velikovsky-type scenarios also seem unlikely. (WRC)

Lamina-counts from the Burmese Tertiary. The scientific paper employed here is rather old (1925); but, since its conclusions depend only upon the measurements of sediment thicknesses and the counting of laminae, the passage of time should not be important in assessing the paper's validity.

The paper's author was L.D. Stamp, who thoroughly analyzed the Burmese Tertiary while searching for oil. Stamp found the fine, rhythmic layers making up the thick marine deposits of the Burmese Peguan an irresistible challenge. The Burmese Peguan is composed predominantly of clays, shales, and sandstones; total thickness, about 12,500 feet; total laminae, about 2,170,000. Stamp thought that each doublet in the Peguan was a varve, although he understood this was an assumption. After considerable counting, Stamp arrived at a set of conclusions, three of which are of interest to anomalists:

"(1) The duration of the Oligocene and half of the Miocene is probably in the neighborhood of 2½ million years. This figure is not inconsistent with the results obtained by the study of radioactive phenomena in igneous rocks." (R8) Today, geologists figure that the Oligocene and half the Miocene spanned about ten times Stamp's estimate, as determined by radiometric dating. On the other hand, Stamp's conclusion is consistent with estimates of geological time based upon measurements of present-day sedimentation rates. (See ESR1-X9.)

"(3) A million years has sometimes been regarded as a mere bagatelle in geological time. In Burma it has been sufficient for the deposition of between 5,000 and 10,000 feet of sediment."

"(4) Due attention to the counting of laminae in sediments may eventually render it possible to determine the duration of geological periods with considerable accuracy." (R8) It goes without saying that radiometric dating has completely superceded dating by studies of sediments.

Other Tertiary rhythmites. The following occurrences of rhythmic bedding must be only of small sample of what actually exists.

"Four well-marked Eocene sedimentary cycles in the Central Gulf Coast area, each due to a major invasion of the sea into the Mississippi embayment, have been described by Bornhauser. Each cycle consists very broadly of a basal marl, calcareous shale, and glauconitic sand, grading up through dark shale into sandstone, shale, and lignites." (R22)

"The Eocene of north-west Europe also displays large-scale cycles of sedimentation. A single basin, probably open to the north-east, extended over most of southern England, northern France, and Belgium, and periodic transgressions and regressions of the sea took place throughout the Eocene. Each of the six resulting cycles, of regularly alternating marine and continental beds, consist principally of clay, but started and finished with coarse clastic sediment." (R22)

"The Cretaceous and early Tertiary sediments of Gubbio (Italy) contain sedimentary cycles of several orders. Basic bedding is caused by limestone marl fluctuations on the scale of a few centimetres and these form groups or bundles with thicknesses of 30-200 cm. Such cycles in turn can form higher-order groups several metres thick. It has been suggested that the cyclicity is the record of climatic variations which are ultimately related to astronomical variables." (R67)

Cyclic bedding has also been observed in pure carbonate rocks, Oligocene in age, from south-central France. (R23)

X3. The Cretaceous Period.

Milankovitch signals widespread during this period. The farther back in geological time we detect Milankovitch periodicities, the surer we can be that the earth's orbital characteristics have remained unchanged. T.D. Herbert and A.G. Fischer found Milankovitch signals in the Cretaceous black shales of Italy.

"The Earth's orbital variations, reflected in Pleistocene ice volume, were also recorded in non-glacial times. Carbonate production in pelagic mid-Cretaceous sediments, quantified by calcium carbonate and optical densitometry time series, reflects the orbital eccentricity and precessional cycles. Minimal eccentricity brought deep-sea anoxia. Most of the sedimentary variability of this 100-Myr-old sequence lies within the Milankovitch (orbital) frequency band." (R64) These marine sediments showed strong 100,000- and 400,000-year periods, reflecting the two orbital eccentricity rhythms. (R65)

In the U.S. Western Interior, in the Upper Cretaceous Niobrara Formation, A.P. Laferriere et al found a more complex situation. We quote from their Summary.

"Occurrence of isochronous rhythmically deposited beds throughout a large area of the Western Interior strongly supports the hypothesis that Fort Hays depositional cycles are climatically induced. However, the observed patterns of cyclicity deviate from the bundles of five shale-limestone couplets that would be expected from a simple precession-eccentricity model of orbitally induced climatic variations. Complications in the cyclic pattern leading to predominantly three-bed and seven- to nine-bed patterns may have resulted from the interference of parameters having different periodicities." (R69; R81)

The bundles of five couplets mentioned above by Laferriere et al are the result of the 21,000- and 100,000-year precession-eccentricity variations. But they think that this idealized situation was upset by interference from the 41,000-year obliquity cycle; but some other, unknown factor could have been involved. Another interesting facet of these deposits is the increase in the number of shale-limestone couplets per bundle as one travels westward. (R69)

The rhythmic deposition of flint in chalk. The flint nodules in the chalk deposits of Europe tend to occur in rhythmic layers. For details, see ESA3-X2, in another volume of this Catalog. (R6)

The Cretaceous chalk cliffs of Normandy, France, consist of alternating layers of chalk and chalk nodules. Each cyclic bed is thought to represent about 20,000 to 40,000 years of sedimentation. Periodic changes in sea level, causally linked to the earth's orbit, may have been the driving force. (R54)

Cretaceous cyclothems in eastern Utah. Although these cyclothems do not cover the immense areas of the coal-bearing, Carboniferous cyclothems of the U.S. Midwest, the mainstream explanation for each is identical. A.J. Wells elaborates.

"Well-developed cyclic deposits have been described by Young from the upper Cretaceous of eastern Utah. In each cycle, four sedimentary facies are recognized, corresponding to the off-shore marine, littoral marine, lagoonal-paludal, and terrestrial environments. In response to relative sea level changes, these environments moved first landwards and then seawards, resulting in an intricate interfingering of the different facies. Each cyclothem is assumed to begin with a rapid transgression and deposition of marine shale. A sand bar or beach forming at or very near the line of maximum transgression graded seaward into silt and mud, and as the beach grew seawards, it rested on mud. Where seaward growth continued long enough a broad apron of sand resulted. Lagoons, flanked by small coal swamps, formed behind the bar and as these became filled with sediment, extensive coal swamps spread over the lagoonal area. If the subsequent transgression was only a minor one, a new sandbar formed on top of the previous one and the coal swamp was not destroyed. On the contrary, a series of minor transgressions produced unusually thick coals." Wells considered these Utah cyclothems to be miniature versions of the great Carboniferous coal measures. (R22) Even with Wells' attractive scenario, the U.S. Midwest Carboniferous coal-bearing cyclothems still pose problems of explanation. See ESC14, for example.

X4. The Jurassic Period. Like the later geological periods chronicled above, the Jurassic abounds in rhythmic sediments, including many with evaporites.

More Milankovitch signals. In Jurassic times, geologists believed that a huge lake stretched across New Jersey and eastern Pennsylvania into New York. "The lake swelled and shrank with changes in climate, depositing varved, organic-rich layers during high stands. Paul Olsen of Yale University used these varves to determine that cycles in the type and rate of sedimentation had periodicities of 18,000 and 24,000 years (precession actually has two cycles of 19,000 and 23,000 years), 101,000 years, and 393,000 years (eccentricity also has a cycle of about 400,000 years)." (R54)

R.A. Kerr, who provided the above quotation, mentions still another case of rhythmic sedimentation from the Jurassic in another article.

"Michael House of the University of Hull has reported evidence of an approximate 40,000-year cycle in the 200-million-year-old marine sediments exposed near Lyme Regis on the southern coast of England. This cycle, says House, is likely related to variation in the tilt of the Earth's axis." (R65)

In his 1986 review of climatic rhythms recorded in the strata, A.G. Fischer mentioned rhythmic bedding seen in platform limestones from the Upper Jurassic of southern Germany. ((R62)

Rhythmites containing evaporite components. The explanations for rhythmites containing evaporites are the same as those for cyclothems, as described by H.G. Richards for a Jurassic rhythmite from eastern Utah.

"The Carmel Formation, a marginal marine deposit of fine clastics and gypsum, exhibits cyclic deposition in eastern Utah. The cycles are well developed and consist of three divisions: a lower reduced unit of shales, siltstones, and platy limestones, an oxidized middle member of silty shale, and a top member or irregularly bedded gypsum. The probable cause of the cycles is a slow regression of the sea combined with minor periodic advances. Climatic changes are proposed as the mechanism for the re-advances of the sea." (R18)

G.V. Wood and M.J. Wolfe, working in Arabia, came upon another rhythmite with evaporites: "Study of 176 ft. (53.7 m) of core from the Arab/Darb Formation of the Umm Shaif, Abu Dhabi Marine Areas, has revealed a sequence of sediments which can be related to nine distinct cycles of sabkha formation. The sabkha cycle consists of a basal algal grainstone/boundstone (which is interpreted as a shoal) passing upwards through lagoonal dolomite, intertidal algal mat and into a final supratidal development of nodular anhydrite and associated dolomite." (R36) Obviously, rhythmites come in many varieties, although all seem to be best explained in terms of transgression and regression of water. (WRC)

Ribbon radiolarites. Since the ribbon radiolarites reached their peak during the Jurassic, we record them here. They are known, however, from many other geological periods. We rely upon P.J. Smith at this point.

"Ribbon radiolarites are rocks that derive their name from their characteristically repetitive bedding---they comprise layers of radiolarian chert (grossly recrystallized radiolaria in a microcrystalline quartz matrix) centimetres to tens of centimetres thick, usually alternating with layers of argillite (clay) generally no more than a few millimetres thick. Complete sequences are typically tens to hundreds of metres thick." Smith admits that the chert-argillite couplets consititute a puzzle. Furthermore, no one has ever found rocks in present-day ocean basins that even remotely resemble the ribbon radiolarites. (R55) Radiolarians are creatures of the deep oceans. The cause of the layering is therefore probably unrelated to marine transgression-regression cycles.

Rhythmic bedding and diagenesis. Cyclic bedding has long been recognized in Europe. (R22) However, in discussing the origin of the limestone-shale rhythm in the Blue Lias of England, A. Hallam introduces a new complicating factor: diagenesis, or the alteration of sediments after they have been deposited. The alternation of bands of limestone and shale are strikingly regular in the Blue Lias. Hallam ventures that a short time after mixed clay and calcium carbonate were deposited: "...a process of rhythmic unmixing began, involving solution and reprecipitation of part of the carbonate fraction. $CaCO_3$ tended to segregate into thin bands of limestone in the midst of marl and shale, accentuating certain primary rhythms and creating others." (R28) If such diagenesis is important in rhythmic bedding, the common explanations of cyclothems and, especially, Milankovitch-type rhythmites might well be compromised; that is, false rhythms might be interjected by mechanisms having no relation to transgression-regression cycles. (WRC)

X5. The Triassic Period.

Milankovitch rhythms in Alpine platform limestones. "Schwarzacher first noted the now well-established ratio of five couplets to a bundle. Fischer established the origin of the cycle as one of periodic emergence, with the cycle leading from a weathered zone through intertidal sabkha-type sediments into subtidal (lagoonal) limestones, succeeded most commonly by another disconformity, but passing in some cases through a regressive sabkha phase into another transgression. Intertidal-subtidal couplets, averaging 5 m in thickness, are bundled into sets of about five. The number of such cycles in the Norian-Rhaetian has not been properly established, but it would seem to lie around 300, and some cycles may not have been preserved. The period is surely in the Milankovitch band, and the pattern suggests the precession index. A eustatic oscillation seems highly likely as the cause, but no evidence for this has been found outside the European Tethys." An interesting aspect of these Triassic rhythmites is that they were laid down in a period which provides geologists with no direct evidence of glaciation. The occurrence of Milankovitch rhythms is thought to be closely linked with climatic changes that cause glaciation and changes in sea level. (R62)

Triassic cyclothems. The Moenkopi Formation of Arizona and Utah contains at least seven cyclothems. This formation is marine in the west and continental in the east. Interfingering of the two types of sedimentary environments has produced cyclothems of marine limestones, calcareous siltstone, mudstones, and sandstones. (R22) It must be reemphasized here that cyclothems may exhibit Milankovitch rhythms and, in fact, be the result of climatic oscillations. (WRC)

X6. The Permian Period. With Permian Period, we are now at the beginning of the Paleozoic, in our downward search for rhythmites in the Stratigraphic Record. The top of the Permian is dated at about 245 million years.

Climatic influences detected in the evaporites of the Castile Formation. In the Permian, west Texas and adjoining New Mexico were occupied by the Delaware Basin, which contained a 14,000-square-kilometer lagoon. A.N. Strahler describes the great evaporite deposits now found in this region.

"These evaporites display a remarkable system of laminations in which couplets consist of one lamina of calcite and one of anhydrite; in another part, the couplet consists of one lamina of anhydrite and one of halite. Roger Y. Anderson and his team of researchers completed a study of the Castile evaporites in which 260,000 couplets were counted in a total thickness of approximately 450 m. Laminae extend for distances as great as 113 km. The couplets are interpreted as varves, but the authors note that this interpretation has never been conclusively demonstrated." (R66)

R.A. Kerr mentioned the Castile Formation in a 1983 article in Science. Here, the laminations were said to be the consequence of the alternation of seasons. This would make them bona fide varves. Kerr stated that the amount of calcium sulfate in the laminae varied in a cycle of about 20,000 years---apparently due to climatic variation. (R54) Thus, even in the Paleozoic, Milankovitch signals persist.

In another volume of this Catalog, the laminae of the Castile Formation were introduced as examples of large-area deposits that maintain constant thickness and character over huge areas. See ESD9-X16. (WRC)

Coal-bearing cyclothems in the Lower Permian of India. The Lower Permian is immediately above the Carboniferous, where cyclothems containing coal strata are most common. S.M. Casshyap has provided a brief sketch of some Indian coal measures dating from the Permian.

"This study corroborates the earlier view that the Barakar coal measures (Lower Permian), as examined in 14 'Lower' Gondwana coalfields, is largely of cyclic nature. An idealized standard sedimentary cycle is proposed which, in the vertically upward sequence, comprises the following lithological types: (A) pebbly, very coarse sandstone, (B) coarse to medium sandstone, (C) fine sandstone, (D) interbedded assemblages of fine to medium sandstone, siltstone and shale, (E) carbonaceous siltstone and shale, (F) coal, shaly coal." (R37) It will be interesting to compare this Permian coal-bearing cyclothem with those of the Carboniferous.

X7. The Carboniferous Period. Below the Permian lies the Carboniferous Period, so-named for the frequent occurrence of coal strata in deposits of this period. American geologists divide the Carboniferous into the Pennsylvanian (286-320 million years ago) and the Mississippian (320-360 million years ago).

Overview of Carboniferous cyclothems and the possibility that Milankovitch cycles persist. The following quotation is from A.G. Fischer's 1986 review of rhythmic deposits.

"The Carboniferous System, especially the Middle and Upper Pennsylvanian, is distinguished in many places by cyclic sequences in which various types of sediment alternate in regular and repeated patterns. Nowhere are these cycles more striking than in the interior of North America. In Illinois, a typical cycle begins with alluvial channel sandstones, followed by an underclay on which rests a coal, in turn succeeded by marine shales containing a limestone and possibly ending in brackish or limnic shale. To such sequences, which record transgressive cycles, Wanless & Weller applied the name cyclothem. Whereas Weller favored a tectonic driver, Wanless & Shepard appealed to eustatic fluctuations engendered by the rhythmic growth and decay of the Carboniferous ice sheets, a view that has been recently championed by Crowell." (R62)

Fischer continued his survey of the Carboniferous by noting that some of the Kansas cyclothems could be bundled together to form a still larger repeating sequence called a megacyclothem. The Kansas cyclothems are younger than the Illinois cyclothems. The marine portions usually contain three to five limestones. It has been suggested that each of these cyclothems is about 500,000 years old, while each of the contained limestones is about 100,000 years old. Therefore, in the Kansas cyclothems we may see both the long (400,000-year) and the short (100,000-year) eccentricity cycles. (R62) This detection of Milankovitch signals so early in the Stratigraphic Record is most interesting, for it implies that some 300 million years ago, before the onset of continental drift, the earth's orbital parameters were much as they are today. (WRC)

Worldwide occurrence of the Carboniferous cyclothems. Although the Carboniferous cyclothems are best-developed in the North American interior, they are also seen in the coal measures of South America, Europe, India, Australia, and Africa. This global synchronism has puzzled geologists for decades, as in this quotation from J.R. Beerbowee.

"The extremely wide geographic distribution of Carboniferous and early Permian cyclothems suggests that causal factors should be worldwide in extent. Some sort of catastrophic mechanism might be possible; Weller postulated a mechanism involving cyclic expansion and contraction of a subcrustal layer. It is easier, however, to visualize worldwide eustatic and/or climatic controls similar to those currently in action." (R24) The last sentence is, of course, a statement of uniformitarianism. In this Catalog, all options are left open, even though the uniformitarian explanation---the "easier" explanation---seems reasonable here. (WRC)

The "fireclays" or "underclays" of the coal measures. Before exploring the full-fledged, many-element, coal-bearing cyclothems, we mention the century-old debate about the nature of the so-called "fireclays" or "underclays", which are found immediately under many coal seams. These fireclays are highly refractory, often contain stigmaria (the supposed rootlets of ancient trees), and are generally thought to be the soil in which grew the plants that went into the formation of the coal directly above. The diversion here has significance because fireclays are integral elements of most Carboniferous cyclothems.

The first question to arise asks if coal seams and fireclays are always found together. The answer is: no. To illustrate, at the South Joggins coal measures, in Nova Scotia, one finds a section almost 3 miles thick, containing 76 coal seams and 90 underclays. It is obvious that fireclays can occur without coal. (R1) Further, coal itself, on rare occasions, does rest directly upon sandstone, without underclays at all. (R3)

To the above facts, we must add that both underclays and coal seams reach great thicknesses. Underclays in England may exceed 30 feet in thickness; whereas one Australian coal seam is some 800 feet thick. (R3 and ESD3-X7, respectively) It is hard to conceive of in-situ origins for such thick formations. T.C. Hopkins considered the fireclays to be transported deposits. (R3)

A final question involves the underclays of present-day peat beds. These underclays usually contain marine shells as fossils. The underclays of the coal measures, on the other hand, do not. Since the modern mainstream view of coal formation envisions an in-situ origin, with peat bogs often cited as modern coal formations in the making, the marine fossils in the peat-bog underclays present a contradiction. (R1) In fact, the evidence of the fireclays led at least one scientist, G.W. Bulman, to claim that the fireclay-coal couplets were actually varves! (R4)

We can see from this short treatment of fireclays the sorts of questions that can arise when couplets of specific strata are repeated over and over again. The full-fledged cyclothems in North America are even more thought-provoking. (WRC)

The great coal-bearing cyclothems of the U.S. interior. Repetitive bedding has been recognized for over a century, as in the case of the remarkable sequence of coal-fireclay couplets at South Joggins mentioned above. It was in the American interior, however, where the cyclothem concept was really born. Let us commence with an overview from a 1989 paper by G. deV. Klein and D.A. Willard.

"Cyclic patterns of transgressive-regressive deposition of marine and nonmarine coal-bearing strata are the distinguishing characteristic of Pennsylvanian sedimentation. Udden (1912) and Weller (1930) were the first to recognize such lithological cycles in Pennsylvanian rocks of the Illinois basin; these were arranged into ten members representing nonmarine and marine deposition. Weller (1930) named these cyclic packages 'cyclothems.' Later workers recognized this cyclic pattern in the Appalachian basin and in the continental interior of the midcontinent. These Pennsylvanian cyclothems differed from the ideal cyclothem of the Illinois basin; cyclothems in Kansas were characterized by extensive marine deposits, with subordinate coal and sandstone, whereas the cyclothems of the Appalachian basin were dominantly nonmarine, with thick sandstones, thicker coals, and minimal limestone. Later workers recognized three types of cyclothems, known as the Illinois type, the Kansas type, and the Appalachian type.

"Extensive controversy has existed about the origin of Pennsylvanian cyclothems. Weller advocated a tectonic control for the formation of the cyclothems, whereas Wanless and Shepard (1936) and Wheeler and Murray (1957) argued strongly for a climatically controlled eustatic origin driven by glacial processes that existed during Pennsylvanian time. These glacioeustatic sea-level changes caused shifting of shorelines that were composed primarily of extensive shallow deltaic systems which migrated over wide areas. Moore (1950) argued that these sea-level fluctuations which formed cyclothems were tectonically induced by changing volume of ocean basins." Klein and Willard contend that the North American cyclothems are due to "a remarkable coincidence of supercontinent development, concomitant glaciation and eustatic sea-level change, and associated episodic thrust loading and foreland basin subsidence." (R84)

For specifics on the North American cyclothems, we go to J. Woodmorappe, who advocates a flood-type origin. His introduction to these formations is excellent.

"There exist among sedimentary rocks certain types which have very many types of rock, in thin layers, which lie on top of another and repeat in a regular sequence. Much of the world's coal is found in such repeating layers. Each repetitve sequence (between coals and including one coal) is called a cyclothem. A diagram of an 'ideal' or 'complete' cyclothem found in Illinois is found in Figure 1. (The reader of this paper should always refer to Figure 1 [p. 94] whenever the number or the lithological identity of a given member is described in this text.) The numbering and termination of the cyclothems differ, relecting the disagreement among Pennsylvanian stratigraphers as to where one cyclothem 'ends' and a superjacent one 'begins.' [Thus, some consider a new cyclothem to begin at the basal sandstone, member 1, while others consider a new cyclothem to begin with the coal (member 5)].

"It must be hastily added that almost never in the earth does a 'complete' cyclothem occur at any location as shown in Figure 1. A real field situation as exists might have this type of layering: members 1, 2, 4, 5, 10, 1, 2, 4, 5, 8, 10, 1, 2, 3, 4, 5, 6, 7, 8, 10, etc. The important fact to realize is that the relative order of the members always exists and that these members do repeat themselves consistently.

"The cyclothems are asymmetrical, which means that the coal or shale (or any other member) may be vastly thicker or thinner than the corresponding member of the cyclothems above and below it. Furthermore, even within one cyclothem, the thickness or thinness of one member does not guarantee the thickness, thinness, or even presence of another member in that cyclothem at all. Six or more of these members are usually found at any given locality and their relative order is always preserved. 'The average thickness of a cyclothem in the central states is less than 50 feet...'

"Although cyclothems and their valuable coal beds are found in many parts of the world, this paper will concentrate on the cyclothems found in Illinois as far as their morphology and specifics are concerned. The Pennsylvanian sediments in the basin cover an area of approximately 55,000 square miles, chiefly in Illinois, Indiana, and Kentucky, with minor areas in Missouri and Iowa.

"The maximum thickness of Pennsylvanian sediments, more than 2800 feet, occurs in the southern part of the basin in Kentucky. Shale is the predominant unit of the sequence with subordinate amounts of sandstone and much smaller amounts of limestone and coal. The presence of ordered lithological sequences or cycles is the most characteristic lithological feature of the Pennsylvanian sediments. More than 50 such sequences are recognized.

"Cyclothems are variable not only in terms of presence of members and thickness of members, but also in terms of lateral extent of each of the members. Some members can be traced for hundreds of miles while others wedge out (& thin out) in only a few miles or else grade into members elsewhere. Many of the cyclothems are nearly as varied within a single county as within the entire state of Illinois.

"For this reason, a detailed study of only a small area may leave the impression that the beds vary greatly, whereas a more general survey of almost the entire Eastern Interior Basin has revealed that the Pennsylvanian system throughout this region is remarkably uniform." (R47)

A marine-nonmarine thickness cycle in Great Britain. The Carboniferous coal-bearing cyclothems in Great Britain are not as well-developed as those in the interior of North America. Even so, a unique type of periodicity has been claimed for the repeating series of limestones, shales, sandstones, and coals located in Dumfriesshire. Using the log from a 3,450-foot-deep borehole, B.W. Carss and N.S. Neidell found that they could easily distinguish between marine and nonmarine elements of the cyclothems penetrated by the drill. Employing only these two characteristics, they detected a thickness cycle of 145 feet. The following paragraph is taken from their 1966 paper in Nature.

"We believe that we have detected a fundamental cycle of about 145 ft. in the vertical change of sea level during the Lower Carboniferous period in Great Britain. Our data were taken from the lithological log of the Archerbeck borehole, Canonbie, Dumfriesshire, and processed by means of the technique of polarity coincidence correlation frequently used in the field of communications engineering. This preliminary result leads to many interesting speculations about the origin and implication of such a cycle. Although changes in the position of the Earth's spin axis might be responsible for such a phenomenon, we favour an explanation in terms of an isostatic mechanism of readjustment." (R32) It is hard to judge the validity of the conclusion of this paper without further studies of a similar nature. All we can say is that analytical techniques from other disciplines may extract unexpected information from cyclothem dimensions. (WRC)

Carboniferous cyclothems without coal members. As the coal-bearing cyclothems were being deposited all over the planet during the Carboniferous, different rhythmites were being laid down nearby.

In New Mexico, Pennsylvanian limestones in the southeastern range of the Sangre de Cristo Mountains exhibit distinct cyclicity. The cyclothems range from 10 to 100 feet in thickness. From base to top, the repeating members are: "(1) biohermal limestone; (2) calcareous shale with interbedded thin undulatory limestone; (3) carbonaceous claystone, siltstone, and sandstone." (R21)

A similar cyclic pattern is also evident in the Pennsylvanian limestones of northeastern Nevada. (R19)

Of more than passing interest are oil-bearing shales found in Scottish cyclothems. J.T. Greensmith sketches them in the following paragraph.

"The Oil-Shale Group of Scotland is a distinctive facies of the Lower Carboniferous Calciferous Sandstone Series and consists mainly of non-marine limestones, sandstones, and shales. Its distinctive character, however, is due to the presence of oil shales which form about 3 percent of the total succession. The oil shale seams are most common immediately to the west of Edinburgh where they are interbedded with approximately 5,000 feet of other sediment..." (R27) One naturally wonders where the oil came from. Was it formed in situ, or did it migrate from elsewhere? (WRC)

X8. The Devonian Period.

Cyclic sedimentation in eastern North America. A 100,000-year cycle has been discovered in the Upper Devonian Catskill Delta deposits, which extend more than 100 kilometers from New York through Pennsylvania into Virginia and West Virginia. J. Van Tassell ascribes this rhythm to cyclic sedimentation forced by climatic variations which, in turn, were caused by the 100,000-year cycle in the eccentricity of the earth's orbit. A tectonic explanation was rejected because of the unlikelihood that the land would "bob up and down" with a regular period of 100,000 years for millions of years. (R76)

Fluviatile cyclothems in the Lower Old Red Sandstone, Great Britain. The Lower Old Red Sandstone is a thick continental deposit of Lower Devonian age. In South Wales, it is 7,000 feet thick; in Shropshire, it has thinned to 3,500 feet. It is cyclic in character. "The 'standard' cyclothem shows a scoured surface followed by sandstones grading up into siltstones. From a knowledge of modern sediments, a fluviatile origin is demonstrated for six cyclothems studied in detail. The scoured surface beneath each cyclothem seems to have been eroded by a wandering river. The sandstones, often with large scale cross stratification, appear to be channel deposits accumulated through lateral and (or) vertical accretion. The siltstones are often interbedded with thin, relatively fine-grained sandstones overlying suncracked surfaces. They are probably floodplain top-stratum deposits representing levee, backswamp and crevasse-splay environments." Three possible explanations were offered for the cyclothems: (1) wandering rivers; (2) varying base levels of the Devonian sea; and (3) varying tectonic activity at the sediment source. (R27)

X9. The Silurian Period.

Cyclic sedimentation in eastern Pennsylvania. At Schuylkill Gap, one sees a striking red-banded rhythmite in the Silurian Clinton Formation. N.D. Smith has described 16 completely exposed cyclic units. "The units range from 15 to 32 feet in thickness and consist of three main elements. In ascending order they are: (1) a basal erosional surface, usually overlain by a thin coarse basal deposit; (2) a sequence of thinly interlaminated greenish-olive shale and sandstone; and (3) red burrow-mottled argillaceous siltstone." Smith suggested that these rhythmic sediments have been deposited in an intertidal zone and represent alternating high tidal flats and either low tidal flats or tidal creek channels. (R34)

X10. The Ordovician Period.

Limestone-dolomite cycles in Maryland. "Cyclic repetition of limestone and dolomite was studied in a railroad cut near Charlton, Maryland. 35 cycles were recognized, each composed of a basal dolomite member and an upper limestone member. Field and petrographic evidence suggests a primary origin for the dolomites in the section studied. The cyclic repetition of dolomite and limestone, it appears, was due to tectonism." The thickness of the section studied was 43 meters. (R26)

X11. The Cambrian Period.

"Grand Cycles" of sedimentation in North America. The large-scale sedimentary cycles of the Cambrian, called Grand Cycles, have been identified in Canada's Northwest Territories (R63), in the Rockies, in the Great Basin, and in eastern North America. For an overview, we quote a paragraph from a 1987 paper by N. Chow and N.P. James.

"Extensive Cambrian-Ordovician shallow-shelf sediments fringe the North American craton and are characterized by prominent large-scale cycles, termed 'Grand Cycles'. These cycles, 90-600 m in thickness, are apparently products of passive continental margins in which carbonate-dominated sedimentation alternated with siliciclastic-influenced sedimentation. As outlined by Aitken, Grand Cycles characteristically consist of a lower unit of fine-grained terrigenous mudstone and limestone and/or sandstone which passes gradationally upward into an upper unit of predominantly limestone and dolomitized limestone. Cycle boundaries are generally abrupt stratigraphic contacts, and each cycle includes two or more trilobite biostratigraphic zones. Grand Cycles were first described in detail in the southern Canadian Rocky Mountains. The concept was subsequently applied to detailed studies of Cambrian strata in the Great Basin, and in the Northwest Territories. In eastern North America, however, only cursory examinations of Cambrian cycles were conducted in the southern Appalachians." (R68)

Following these generalizations, Chow and James detailed the Grand Cycles as they are found in Newfoundland. They attribute all Grand Cycles to a eustatic mechanism. The first step in their formation is a rapid rise in sea-level, resulting in muddy tidal flats. In the second stage, ooid shoal complexes encroach upon the tidal flats. Several causes are suggested for sharp rises in sealevel: glacial melting, changes in the distribution of ocean water due to fluctuations in rotation and gravitation (geoidal eustasy), and changes in the volumes of the ocean basins resulting from tectonic activity. (R68)

X12. The Precambrian Period. The great terrestrial upheavals that marked the Precambrian-Cambrian transition have made it difficult for geologists and paleontologists to decipher exactly what happened prior to about 650 million years ago. Yet, progress is being made. A unique source of information about the Precambrian earth comes from some remarkable deposits of rhythmites.

Late Precambrian rhythmites in South Australia. There was considerable scientific excitement in 1981. when G.E. Williams announced that he had discovered the sunspot-cycle signal in varves about a periglacial lake in the Flinders Ranges in South Australia. (R51, R52, R58, R59) Besides the sunspot signal (10-14 "years"). cycles of 22-25, about 105, about 157, and about 314 "years" were also detected. Quotes are employed around the word years, because Williams made the assumption that the sedimentary layers he was measuring were true varves; that is, annual deposits.

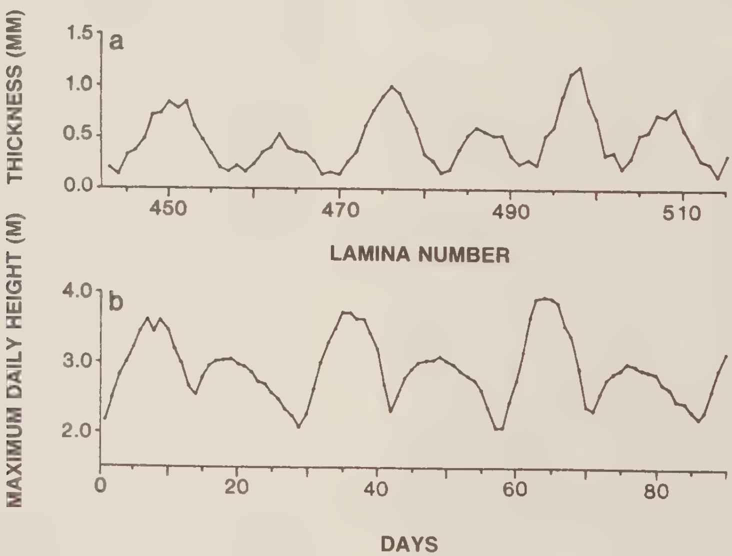
By 1988, however, Williams had decided that the laminae were not varves but rather records of the fortnightly lunar tidal cycle. This turnabout was stimulated by the analysis of another group of rhythmites near Adelaide. There, Williams discerned cycles of 14 or 15 laminae per cycle---the fortnightly tidal cycle. At present, Williams believes that both Australian rhythmite deposits are tidal in character. In sum, the sunspot/weather connection has been discarded in favor of a long, detailed tidal record that may reveal important facts about the dynamics of the earth-moon system in the Precambrian. (R71, R72, R77)

In 1989, Williams published a lengthy paper in Eos detailing his research and conclusions, as of that date. Below, we quote two paragraphs that describe the rhythmites and the various cycles observed. Following these paragraphs, we quote Williams' conclusions as to the import of the rhythmites on our knowledge of the ancient earth-moon system.

"Siltstones and fine sandstones of Marinoan age (~ 650 Ma) within the Adelaide Geosyncline in places display rhythmic lamination that records a complexity of cycles. The rhythmites are particularly well seen in a ~10-m-thick member of the Elatina formation at Pichi Richi Pass in the Flinders Ranges. They are well exposed also in coastal sections of the correlative Reynella siltstone at Hallett Cove some 300 km to the south near Adelaide. Similar rhythmites also occur in siltstones and fine sandstones of the Chambers Bluff tillite of possible Sturtian age (~800 Ma) in northern South Australia. These rhythmites together may encode rare celestial signals from Precambrian time."

Rhythmite details: "In essence, graded (fining-upward) laminae ~ 0.2 to 3.0 mm thick that can be traced laterally for hundreds of meters are grouped in conspicuous 'lamina-cycles' containing an average 12 (±1.6 s.d.) laminae over a measured sequence of 1337 lamina thicknesses. Lamina-cycles are bounded by darker, clayey bands where thinner laminae crowd together. The plot of lamina thickness [see figure] shows a characteristic alternation of high- and low-amplitude cycles."

From Williams' Abstract: "The rhythmites may provide unique information on paleotidal periods and Earth's paleorotation: the late Precambrian year contained in ~13.1 (±0.5) lunar months and ~400 (±20) days, and the late Precambrian lunar month ~ 30.5 (±1.5) days; the periods of the lunar apsides and lunar nodal cycles were then 9.7 (±0.3) and 19.5 (±0.5) years respectively. These values suggest that since late Precambrian time the average equivalent phase lag (the angle between the Earth-Moon axis and Earth's tidal bulge, derived from the response of the solid and ocean tides) was near 3° rather than the present value of



(a) Thickness of laminae from the Elatina series, showing cycles of alternating thickness. (b) Maximum daily tide heights for the first quarter of 1966 from Townsville, Queensland. (X12)

6°. Precambrian sedimentary rhythmites may record much valuable information on the early history of Earth's rotation and the lunar orbit." (R79)

Cyclic sedimentation in southeastern Minnesota. "The Solor Church Formation of Late Keweenawan (Late Precambrian) age occurs in the subsurface of southeastern Minnesota where it comprises an integral part of the St. Croix horst, the major structure that underlies the northern part of the Midcontinent Gravity High. The formation consists of intercalcated red intraformational conglomerate, sandstone, siltstone, mudstone/shale, and lesser amounts of limestone. The clastic rocks were derived from a dominantly basaltic terrane much like that which now flanks and underlies the formation. The limestones have a limited distribution and consist of admixed oolites and various kinds of intraclasts indurated by a sparry cement or a micritic groundmass.

"Two kinds of sedimentary cycles, each characterized by 'fining-upward' attributes, are recognized in the Solor Church Formation. (1) Minor cycles, 3-50 ft thick, which consist of a sandstone/conglomerate facies overlain by a siltstone/mudstone facies. Each minor cycle contains a vertical succession of primary structures and textures indicative of alluvial sedimentation. (2) Major cycles, which may be as great as 600 ft thick, are characterized by a systematic increase, stratigraphically upward, in the amount of mudstone relative to sandstone." The author of this paper, G.B. Morey, believed that this cyclic sedimentation was deposited by rivers flowing on an alluvial plain. The cyclic nature was thought to have been forced by "periods of tectonism". (R42) But why should tectonism be periodical? The 600-foot-thick "cycles" likewise pose questions because of their size. (WRC)

Banded iron. Banded iron deposits pose several problems for the geologists of the Precambrian. How can microscopic lamina persist over 100 and more miles. How did such deposits originate in the first place? Since the banded-iron phenomenon has already appeared twice in the Catalog of Anomalies, it seems practical to save space here and refer the reader the other other entries. (ESC9-X12 and ESD9-X15)

X13. Theories of cyclic sedimentation. In reading the papers and books listed in our lengthy, but still rudimentary, bibliography, we were struck with the strong tendency of most authors to opt for either climatic or tectonic control of rhythmic sedimentation. The full range of possibilities is rarely explored, in particular those bearing the catastrophic label.

Astronomical cycles are appealed to most often. The interactions of the sun, the moon, and the earth produce a wide spectrum of frequencies. Astronomically induced periods can range from one day to at least 400,000 years. There are the tidal effects on sedimentation, discussed in X12, and changes in insolation, which have produced rhythmites in almost all geological periods. Generally ignored are the possible effects of cyclic catastrophism, due perhaps to the periodic impacts of comets and/or asteroids. Since terrestrial cratering may show a periodicity of about 26 million years, it is possible that some cyclothems are laid down during cyclic marine incursions.

As for purely terrestrial forces, geologists have long wondered if tectonic forces were rhythmic; that is, periodic orogenies and cyclic rising and subsiding of sea coasts. Indeed, in the forgoing entries, such phenomena were often invoked but never explained. Periodic volcanism may also have played a role. One can even envision geochemical and geothermal cycles controlling sedimentation. In fact, we must admit that we know very little about forces at work inside the earth itself. Other chapters in this volume underscore this ignorance.

We cannot digress any longer here to inquire into the myriad of possible natural rhythms. The purpose of this Catalog is the recording of anomalies. In view of the many possible rhythmic forces available to modulate sedimentation, rhythmits can hardly be called anomalous. The crux of the cyclothem/rhythmite problem is the identification of the correct forcing frequency for each rhythmite. (This is not always obvious, as we learned in the case of the Precambrian Australian rhythmites in X12.) Even so, most cyclothems and rhythmites are probably not anomalous, for they do not challenge any geological paradigms.

But, if the Carboniferous, coal-bearing cyclothems were correlated with a short-period rhythm (measured in years rather than millennia), we would have a first-class anomaly. Or, if cyclothems were the consequence of periodic tsunamis, due to comet/asteroid impacts, then we would have another first-class anomaly. Admittedly, these are just radical thoughts. The point is that rhythmites may, upon unfettered analysis, reveal to us startling new facts about the history of the solar system and the dynamics of the earth's interior.

Finally, our literature search has uncovered a scientist with poetic inclinations. Way back in 1917, J. Barrell introduced a long treatise (almost 200 pages long) on rhythms and geological time with a paragraph that is surprisingly appropriate to the above discussion. It is flowery, but apt.

"Nature vibrates with rhythms, climatic and diastrophic, those finding stratigraphic expression ranging in period from the rapid oscillation of surface waters, recorded in ripple-marks, to those long-deferred stirrings of the deep imprisoned titans which have divided earth history into periods and eras. The flight of time is measured by the weaving of composite rhythms---day and night, calm and storm, summer and winter, birth and death---such as these are sensed in the brief life of man. But the career of the earth recedes into a remoteness against which these lesser cycles are as unavailing for the measurement of that abyss of time as would be for human history the beating of an insect's wing. We must seek out, then, the nature of those longer rhythms whose very existence was unknown until man by the light of science sought to understand the earth. The larger of these must be measured in terms of the smaller, and the smaller must be measured in terms of years. Sedimentation is controlled by them, and the stratigraphic series constitutes a record, written on tablets of stone, of these lesser and greater waves of change which have pulsed through geologic time." (R5)

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ESR6 Undisturbed and Unconsolidated Ancient Sediments

Description. Sediments designated as hundreds of millions of years old which are undisturbed and/or unconsolidated and unlithified. In short, they appear young and unmodified by time.

Data Evaluation. Mainly, the scientific creationists have remarked on these phenomena. (This is not surprising because they favor a "young earth".) While mainstream geologists write little on this subject, the examples given below appear accurate and reliable, and the skeptic can always visit Grand Canyon and the other sites mentioned. Rating: 2.

Anomaly Evaluation. If rocks officially designated as "very old" were actually very young, we would have a first-class anomaly. In discussing stratum characteristics such as horizontality, consolidation, and induration, however, one can always claim that the strata in question "just happened to escape" the tectonic forces and the agents of consolidation and lithifaction. Nevertheless, the phenomena remain curious, to say the least. Rating: 3.

Possible Explanations. Some sediments, for unknown reasons, were "lucky" and were not subjected to geological aging processes.

Similar and Related Phenomena. Missing strata (ESR1); deposits of great areal extent (ESD9); radiometric dating discordances (ESP1 and ESP12); tektite age paradox (ESM3-X13); tektite recency paradox (ESM3-X18).

Examples

X1. Undisturbed ancient sediments. Given the immense age of the earth and all the geological traumas that must have transpired during that time, how do geologists account for all of the nicely horizontal, apparently undisturbed sedimentary rock found in many localities? A.W. Mehlert wonders about this, too, in the following quotation, which unfortunately is rather short on specifics.

"...we are assured by mainstream geologists that in the two billion years from the early Archeozoic to the present, just about every square mile of the earth's surface has been subjected to countless contortions, uplifts, downwarpings, depositions, erosions and various other tectonic activities of all violent kinds, over and over again. Mountain ranges have been uplifted and completely eroded away, not just once but many times over. Huge volcanic outbursts and earthquakes contributed to the frequent destruction of topographic features."

.....

"In view of all these countless destructive activities, how is it that we find hundreds, nay thousands of locations all over the Earth where nicely formed, undisturbed sedimentary beds, many of them enormous in size, both vertically and in horizontal area, ranging back to two or more billion years ago, with their embedded fossils, quietly waiting all that time to be discovered by modern paleontologists? What amazing providence perfectly preserved all these sites and shielded them from all the destruction and tectonic activity going on supposedly all over the Earth?" (R2)

A good example of the beds Mehlert talks about may be found in Grand Canyon, where hundreds of millions of years have supposedly passed without disturbing the nice horizontality of many of the most prominent strata. (See ESR1-X4 for details.) Skeptics who question whether we have a viable phenomenon here always state that long-undisturbed strata are remarkable but constitute no anomaly; there is no reason why a few parts of the planet should not have escaped all the traumas mentioned above by Mehlert. Or is this just wishful thinking? (WRC)

X2. Unconsolidated ancient sediments. Following the theme of X1, one would anticipate that hundreds of millions of years would have been sufficient to have consolidated and lithified most ancient sediments, or at least have given them the appearance of great age. However, G.M. Price demonstrated that such expectations are often unfulfilled.

"The very oldest fossiliferous rocks may not only be at the surface, as might be expected in many instances; but some of them remain just as soft and unconsolidated as any of the Tertiaries or the Pleistocene. That is, in all their physical characters they look as young as any of the strata of the entire geological series. 'In the Baltic province and in parts of the United States, the rocks still retain their original horizontality of deposition, the muds are scarcely indurated and the sands are still incoherent.' [Grabau]

"The areas in the United States to which reference seems to be made in this quotation, occur in the Lake Superior region; but it seems that even the Penokee series of this region, regarded as a subdivision of the Algonkian or Pre-Cambrian, is also in the same unaltered and unconsolidated condition.

"The same condition prevails with reference to the Ordovician, which is the system rated as next in age to the Cambrian, 'Across northern Russia Ordovician rocks cover a great area; they consist of clays, bituminous and calcareous shales, sands, and marls' 'They lie flat and undisturbed...the sands and clays are as soft and incoherent as the similar rocks of Tertiary age in the south of England.' [Encyclopedia Britannica]

"The Cretaceous beds of Tennessee,

Mississippi, and Alabama are of the same character. They consist of unconsolidated gravels, sands, and clays, and look as young as any 'late' Tertiary or Pleistocene beds. And while the Cretaceous rocks are not regarded as 'old' geologically, they are sufficiently ancient, according to the current theory, to make it utterly incredible that they could still be in this soft unconsolidated condition. Their every appearance is certainly against the theory of their being millions of years old; while the examples which I have quoted above of Cambrian and Ordovician rocks also in the same condition, is one of the standing wonders of geological science,---that is, in the minds of those who believe the current theories. There is nothing wonderful about any of these examples if we discard the theory of their really being older than the rocks elsewhere which may be classed as Tertiary or Pleistocene." (R1)

Of course, the fact that some rocks have somehow escaped consolidation and lithifaction can be more easily labelled "remarkable" than taken as evidence of a grossly inaccurate geological time scale. (WRC)

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ESR7 The Vertical Stacking of Geological Deposits

Description. The tendency of some geological deposits, notably petroleum and sandstone, to occur in the same vertical section; that is, they tend to be stacked one above the other, often separated by various other types of deposits. Vertical stacking should not be confused with rhythmic bedding and cyclothems (ESR5), for it is not rhythmic nor are the same sequences of sediments repeated.

Data Evaluation. The literature on vertical stacking seems to be virtually non-existent. Rating: 3.

Anomaly Evaluation. There are at least two explanations of vertical stacking: (1) The environment of the deposits (topography, rivers, weather patterns, etc.) is conducive to the episodic deposition of the stacked sediment; and (2) Deeply buried materials seep upward through localized vertical channels (faults in the crust, etc.) and are deposited in this vertical section. The first explanation depends upon surface features to channel specific sediments---episodically---into a sedimentary basin of some sort. Vertical stacking amenable to this type of explanation is hardly anomalous. The second explanation depends upon weaknesses in the earth's crust to channel gases and/or fluids (read "hydrocarbons") into a vertical section. This mode of forming oil deposits is highly controversial. Therefore, the vertical stacking of oil deposits is anomalous. Rating: 2.

Possible Explanations. See above.

Similar and Related Phenomena. Rhythmites and cyclothems (ESR5); the vertical stacking of petroleum deposits (ESC13-X26).

Examples

X1. The vertical stacking of hydrocarbon deposits. Not only do oil deposits display a distinctive geographical distribution (as described in ESC13), but they also often possess another striking geometrical characteristic, as related by T. Gold below.

"It is the vertical distribution of hydrocarbons in any such area; the fact that it is quite common to find every level that the drill passes on the way down to contain oil or gas (Kudryavtsev's rule). The quantities that may be recoverable at the different levels may vary greatly, as porosity and permeability vary, but the entire vertical column has hydrocarbons in its pore spaces. At first sight one might argue that this would just result from a prolific supply at the deepest level. But when, as often happens, the deepest level is in fact the crystalline basement or a very ancient non-fossil-bearing sediment just overlying the basement, then such an explanation seems inadequate." (R2) Gold believes that most hydrocarbons in the earth's crust are abiogenic and originated at great depths.

X2. Multistory sandstones.

"Sandstone formations display a tendency to reflect the geometry of other sandstones which they overlie. A sequence of sandstone layers, separated by layers of shale or limestone, may be thicker above areas where underlying sandstones are thicker, so that two or more lenses of sandstone may occur in vertical alignment. Such a sequence is called a multistory sandstone and is illustrated in [the accompanying figure].

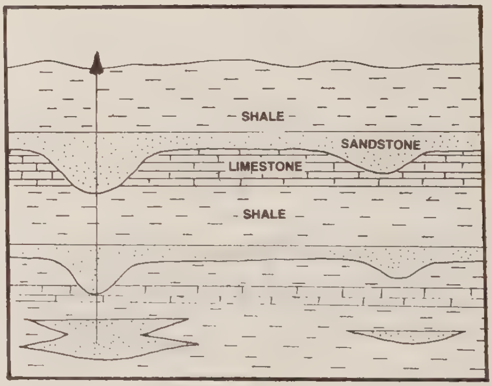
"The uniformitarian interpretation requires that erosion was active immediately above a buried sand, and more sand was deposited in the depression. The hypothetical river, which eroded the upper channel, must have 'remembered' the course of a preceding river, whose channel lay buried deep below. An example of a multistory sequence in the Permian rocks of north-central Texas extends through 1200 feet.

"These thick lenses of sandstone stacked vertically can be explained as follows. Once a sandstone body formed in the shale, the sand provided a conduit for fluids expelled during compaction. The process of sand formation by quartz grain growth was initiated below or above the first sand body, because of convergence of the flow to that region. The flow of pore fluids towards thicker sandstone layers (with higher permeability), where the pore fluid pressure gradient was greater, caused the development of thicker sandstone layers vertically aligned with previously formed lenses." (R1)

References

R1. Cox, Douglas E.; "Sandstone and the Flood Environment," Creation Research Society Quarterly, 22:158, 1986. (X2)

R2. Gold, Thomas; "Where Are Oil and Gas Found?" Power from the Earth, London, 1987, p. 132. (X1)



Multi-story sandstones may form in a sequence of shale, sandstone, and limestone when fluids rise vertically through a sequence of thick sandstone lenses. (X2)

ESR8 Continent-Type Rocks in the Ocean Deeps

Description. Rocks typical of the continents, such as granite and limestone, that are found situated in very deep waters. These rocks may be in the form of isolated boulders, gravels, extensive blocks of strata, etc.

Data Evaluation. Results from many deep-sea dredging and drilling projects confirm the widespread existence of continent-type rocks in the oceans. Rating: 1.

Anomaly Evaluation. The accepted theory of plate tectonics states that oceanic crust is formed as basalt wells up along the ocean ridges, forming conveyor belts of crust that move away from the ridges toward the continents. When continent-type rocks are found far from the continents themselves, in very deep waters, a mechanism explaining their presence must be found. Some possibilities are:

1. Continental debris dropped by icebergs
2. Ballast discarded from ships
3. Continental fragments left behind after the onset of continental drifting
4. The eruption of continent-type rocks from the sea floors

The first three mechanisms on the list are currently acceptable to mainstream geologists, and observations consistent with them cannot be considered anomalous. The third mechanism, in particular, is commonly invoked to explain boulders and blocks of strata too large to be carried by icebergs and ships. The fourth mechanism, in contrast to the first three, would be highly anomalous, because the theory of plate tectonics does not envisage oceanic sources of continent-type rocks. Some data from the Mid-Atlantic Ridge faintly suggest the possibility of such sources. See X6.

Two implications of the phenomenon at hand are also considered anomalous: (1) That blocks of continent-type rocks separated from the continents by wide, deep gaps imply that the ocean-floor conveyor belts are really moving away from the continents rather than toward them; and (2) That the evidence for large vertical changes in the elevation of continent-type rocks in the oceans, including even past subaerial existence, implies that legendary lands like Atlantis might have actually existed. Composite rating: 2.

Possible Explanations. See above discussion.

Similar and Related Phenomena. Terranes and continental accretion (ESR9); topographic arguments against plate tectonics (ETL); the Atlantis question (M).

Examples

X1. Survey of continental-type rocks found in the oceans. M.L. Keith compiled in 1971 a list of islands, submarine plateaus, and other oceanic sites where geologists have found granites and other rocks usually considered continental in origin. Keith's position was that these rocks are actually fragments of continents that have been conveyed away from the continental edges by forces like those active in continental drifting. The problem here is that these purported continental fragments have been transported away from the continents. In contrast, the hypothesis of continental drift states that the ocean-floor conveyor belt carries material away from the mid-ocean ridges toward the continents. Here is how Keith argued.

"Separated segments of continental shelf. A variety of metamorphic and plutonic rocks have been dredged from the crest and flanks of the mid-ocean ridge. Some, including most of those with continental characteristics, have been classed as ice rafted erratics, but one cannot so easily explain the inclusions of granite, syenite, etc., in the volcanic rocks of Ascension Island on the Mid-Atlantic

Ridge or the granite and nepheline syenite blocks of Kerguelen on the Indian Ocean Ridge. Their existence leads one to suggest that there may be segments of continents in some mid-ocean regions.

"A number of separated and subsided shelf areas are known around the margin of the Atlantic. The seaward edge of the Demerara plateau off Brazil is composed partly of shallow-water Jurassic sandstone, now at 4,400 m depth. Similarly, in the north Brazilian submarine ridge, cored by JOIDES hole 23, Miocene ooze about 10 m.y. old rests on a weathered shallow-water algal limestone now at 1,800 m. At Rio Grande rise, some 1,200 km from the South American coast, a lithified shallow-water coquina was cored in hole 21, which was drilled in 2,100 m of water. The coquina is directly overlain by a chalk ooze of Upper Cretaceous age and therefore must be older than about 72 m.y.

In addition, M.L. Keith, the author of the above quotation, identifies several other spots where continental rocks have been detected in the ocean deeps. For example, the Blake Plateau (off Florida) and Orphan Knoll and Flemish Cap (off Newfoundland) possess the geological characteristics of continental shelves. Orphan Knoll is some 500 kilometers from Newfoundland and separated from it by waters up to 2,500 meters deep. Furthermore, Orphan Knoll is built of graded terrestrial sandstone containing fragments of anthracite coal. Farther east in the North Atlantic, Rockall and Lousy Bank, both even farther from the continental shelf also appear to be shelf areas. With these facts in mind, Keith concludes with the following paragraph.

"I contend that the evidence favors the idea that these continental segments represent various stages of shelf detachment and migration away from continents in response to convergent creep. Seafloor spreading from a mid-ocean source does not provide a mechanism for bypassing segments of continental shelf or for moving them away from the continents." (R8)

X2. Galicia bank. Galicia bank is a flat-topped, cliff-like chunk of land, 20-30 miles across. It lies under 2,400 feet of water about 30 miles off the northwest corner of Spain. Magnetometer measurements reveal that it is different from the volcanic seamounts in the Atlantic. Rocks dredged up from the surface of Galicia bank seem to be metamorphic in character and, therefore, of continental origin. Icebergs, however, could have dropped the rocks there.

"The steep-sided topography favors the continental, metamorphic composition, for the bank could then be a block that has been dropped a few thousand feet by a similar kind of faulting which formed the African rift valleys. This solution raises the question of how the block of continental rock got separated by a wide, deep channel from the mainland. It could, of course, be a leftover from the time when the Americas separated from Europe and Africa, as the proponents of the drifting continent theory suppose." (R1)

X3. The Rockall-Faeroe plateau. The tiny island of Rockall breaks the surface of the Atlantic 300 miles northwest of Ireland. Rockall, though, is merely the peak of a huge submarine plateau the size of Ireland itself. In 1969, the research ship RRS *Discovery* brought back evidence that the plateau is composed of sedimentary rocks that may be more than 10,000 feet thick. The water over the plateau is shallow, leading geologists to think that it may be a piece of one of the continents left isolated when Europe and North America separated. (R2)

Seismic data support this view: "Recent seismic refraction experiments in the North Atlantic indicate that the Faeroe Islands are underlain by continental crust. This suggests that the whole Rockall-Faeroe Plateau may be a microcontinent which formed during the early evolution of the North Atlantic." (R9)

X4. The Demerara plateau. Continental rocks have been recovered from depths of more than 2 miles from the Demerara plateau, located off the northeast coast of Brazil. The site of the dredging reported below was about 50 kilometers from the South American coast.

"Abstract. The oldest sediment yet sampled from the abyssal margins of South America, late Jurassic (or possibly very early Cretaceous) shallow-water, coarse-grained, calcareous sandstone containing palynomorphs and mollusk prisms, was recovered from a depth of 4400 meters on the seaward scarp of the Demerara Plateau. The sandstone was deposited in a shallow, late Jurassic epicontinental sea after the initial stages of rifting when the newly created Atlantic began to founder." The "foundering" apparently took place at an average rate of 0.03 millimeters/year over 140 million years. (R3)

X5. The Caribbean Basin. In 1969, the research ship Eastward dredged up large quantities of granite pebbles and boulders from the floor of the Caribbean. Some specimens came from depths of 1,800 meters. Furthermore, seismic surveys of the Caribbean Basin suggest that the entire region is underlain by granite. The Caribbean Basin, therefore, could be a subsided segment of continental crust---a very large segment. This constitutes a problem for proponents of continental drift, because there does not appear to be enough room for the entire Caribbean Basin in pre-drift fits of the continents. In view of this, some geologists believe that the continental rock under the Caribbean was formed about 150 million years ago---after drifting had begun. In this context, it should be realized that, although plate tectonics has hypothesized a mechanism for generating oceanic crust at the mid-ocean ridges, no similar, widely accepted mechanism exists for generating new continental crust. For this reason, the genesis of the entire Caribbean Basin remains a bit mysterious. (R4) Is it foundered relict crust or new, post-drift crust?

X6. The Mid-Atlantic Ridge.

"One of the chief methods of studying the earth's mantle is through analysis of igneous rocks found on the ocean floors. Such rocks presumably originated in the mantle under the ocean. The chemical character of certain rocks exposed on the mid-Atlantic Ridge, however, suggests that though they are derived from the upper mantle, they are not related to modern oceanic basalts, but resemble instead the type of mantle material that underlies the continent.

"The abundance of these rocks in the equatorial mid-Atlantic Ridge, says Dr. Enrico Bonatti of the University of Miami, indicates that there is either a continuous layer or large blocks of continental type mantle imbedded in the mantle under the ridge." (R5)

In 1971, when Bonatti elaborated on his findings in the Journal of Geophysical Research (R6), he suggested that this continent-type mantle was originally part of the pre-drift continent Pangaea. When Pangaea split apart, some of the old continent-type crust remained behind at the ridge. This conclusion is supported by seismic surveys, which reveal a large zone below the mid-Atlantic Ridge where velocities are low.

In 1975, Bonatti, along with four co-authors, published the analyses of dredge samples collected from the mid-Atlantic Ridge in Earth and Planetary Science Letters. (R11) We provide below a short summary of these results as they appeared in New Scientist.

"The limestones include traces of shallow-water fossils---foraminifera, green algae, bits of gastropods, and crab coprolites---implying formation in water, in one instance, less than 30 m deep. Furthermore, the limestones have been recrystallised from a high- to low-magnesium form of calcite. Oxygen- and carbon-isotope ratios prove conclusively that this process must have taken place subaerially 'through the action of meteoric water enriched in light carbon while passing through a soil zone...' A pitted limestone sample bears evidence of tidal action. Some 50 km east of the dredge site along the Vema fracture the team also recovered a thick-shelled, shallow-water, bivalve fossil from a depth of over 2000 m."

The coprolites in the sample yielded a Mesozoic age for the limestone, implying that the limestone could well have been a sedimentary capping on a continental block left behind after the continents split apart. The relict block appears to have been raised above sealevel at some time during its history. (R12) This evidence for large-scale vertical movements led to the New Scientist title of "Concrete Evidence for Atlantis?" Of course, the authors made no such specific claim.

X7. The Mediterranean. The first paragraph of B.C. Heezen's article (below) summarizes the situation in the Mediterranean very nicely---pieces of the continental crust may have dropped far below present sealevel.

"The dredging of schists, phyllites and marbles from the faulted margin of a tilted crustal block in the central Tyrrhenian Sea shows that the acoustical basement beneath the centre of this sea basin includes a sequence of rocks similar or perhaps identical to the Paleozoic and Triassic schists and phyllites of the adjacent Apennine, Calabrian and Sicilian chains. Even the low to medium grade metamorphism observed must have occurred beneath the Earth's surface and following metamorphism and deformation we infer that these rocks were uplifted, denuded by subaerial erosion and finally foundered more than 3,000 m below sealevel. The Neogene subsidence is still continuing. The metamorphic rocks obtained from the Tyrrhenian acoustic basement appear to support the former existence of the Tyrrhenides and indicate that this ancient upland was underlain by continental crust." (R7)

X8. The Gulf of Mexico. Petroleum is usually considered a continental type of "rock". Yet, it has been found at great depths in the Gulf of Mexico. For example, at Site 2, Leg I, of the Deep Sea Drilling Project, cores brought up showed signs of petroleum from the Challenger Knoll 3572 meters down. This oil is stated to have migrated into these deep rocks. (R10) There is another, more heretical theory: namely, that of T. Gold, who maintains that abyssal oil is derived from hydrocarbons seeping upwards from deep in the crust. Such oil would be abiogenic. See ESC13-X28 for more.

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ESR9 Exotic Terranes

Description. Blocks of continental or oceanic crust that possess characteristics suggesting that they originated at locations far distant from their present positions. The characteristics leading to the "exotic" label are primarily the inclination of the remanent magnetic field, stratigraphy, contained fossils, and radiometric age. Some terranes seem to have been transported several thousands of miles from where they originated. Terranes from radically different places of origin are often welded together.

Data Evaluation. During the 1980s, terranes were popular subjects for geological research. Consequently the recent scientific literature is full of papers on this phenomenon. Rating: 1.

Anomaly Evaluation. The fact that terranes are usually "exotic"; that is, they come from different and distant parts of the globe; requires a transportation system that can collect blocks of crust over a wide area of the planet and then assemble them in specific regions, say, western North America. This transportation system is widely believed to be the same as that responsible for the drifting of today's continents. The scientific consensus is that a slow convection of a viscous fluid within the earth's mantle provides this motive power and, in addition, generates the earth's dipole magnetic field. Whether terranes are anomalous or not depends upon whether their seemingly helter-skelter motion through geological time is actually consistent with the fluid convection pattern required to generate the dipole magnetic field. Obviously, this is difficult to assess, but intuitively the past haphazard motion of terranes does not seem compatible with the generation of a stable dipole geomagnetic field. Rating: 2.

Possible Explanations. It is possible that the earth's field has been fairly constant throughout geological time and the belts of diverse terranes just reflect a long history of complex drifting of bits and pieces of crust---planetary flotsam and jetsam! Another, more radical, possibility is that the geomagnetic field has had a very complex history of polar motion and the temporary formation of quadrupole and other fields.

Similar and Related Phenomena. Pieces of continent-type crust in the oceans (ESR8); terrestrial belt-like structures (ESR10); the anomalies of the geomagnetic field (EZ); questions about plate tectonics (ETL).

Examples

X0. Background and introduction. During the 1950s, 1960s, and even into the 1970s, the world's geologists were gradually---very reluctantly at first---accepting the theory of plate tectonics. Today, plate tectonics is a mainstream hypothesis, and even taught in high school.

The facet of plate tectonics that is pertinent to this section is that which pictures the ocean floors as vast conveyor belts moving ponderously from mid-ocean spreading centers towards the continents. As these moving sheets of rock dive under the continents ("subduction"), some of the soft sediments they carry are thought to be scraped off and plastered on the edges of the continents. But now, in the 1990s, this scenario seems simplistic. The edges of some continents, particularly western North America, seem to be collages of heterogeneous blocks of rocks that are unrelated to one another geologically, paleontologically, or magnetically. There are, in fact, hundreds of these exotic chunks of real estate (called "terranes") stacked up against the edges of most continents. Classical plate tectonics seems to be incapable of explaining such diversity and the strong evidence that some terranes have been transported thousands of miles.

Geology, it appears, is due for a new paradigm shift---a major reworking of plate tectonics. The stimulus for this important change in outlook seems to have begun in western North America, where one can stand in one spot and see within two miles three different terranes: continental, oceanic, seamount; all welded together. An article by S. West relates the observations of D.L. Jones.

"In the early 1970s, for example, paleontologists working in Alaska found fossilized remains of extinct single-celled organisms that are foreign to North America but are characteristic of Asia. At the same time Stone and others uncovered paleomagnetic evidence in southwestern Alaska that indicated that those rocks had formed somewhere farther south. 'At that time it wasn't tenable to make the radical suggestion that those rocks had broken off of something in the Pacific so we just had them slide up from the coast near Oregon and Washington,' Stone said in an interview. Other researchers from Canada and Washington began to publish similar sorts of results: 'Everybody had information like that in their files,' says Stone, 'but they just held on to it until somebody had the courage to publish.'" (R4)

The new paradigm, now in an embryonic state, might well be called "microplate tectonics", because instead of continent-size plates it deals with pieces of crust a few miles to perhaps hundreds of miles in extent. The old conveyor belt idea (still without a mechanism) is retained in microplate tectonics. However, rather than transporting huge continents, the conveyor belts somehow collect sundry bits of ocean crust, continental crust, ocean islands, seamounts, etc., and plaster them against the continents. Understandably, it will difficult for mainstream geologists to discard the stately continents of old for patchwork quilts of exotic terranes.

Definition of a terrane. We quote here from a discussion of western North American terranes by P.J. Coney et al.

"The terranes...are characterized by internal homogeneity and continuity of stratigraphy, tectonic style and history. The boundaries between terranes are fundamental discontinuities in stratigraphy that cannot be explained easily by conventional facies changes or unconformity. Most boundaries separate totally distinct temporal or physical rock sequences, and many juxtapose different faunas. Some terranes carry palaeomagnetic records that differ strongly from those of cratonal North America. These data suggest large displacements and/or rotations between the terranes themselves and between the terranes and stable North America.

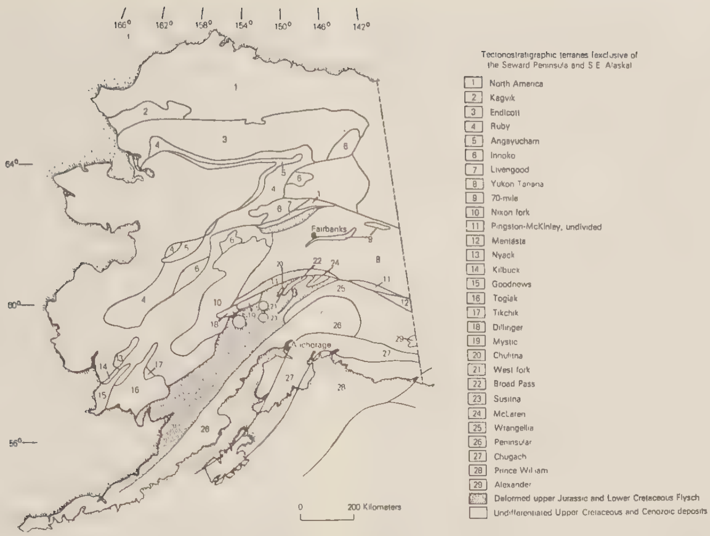
"Note that identification of a terrane is based primarily on its stratigraphy and need not carry any genetic or even plate tectonic implication. At the start of the investigations, the identified terranes are simply considered as domains in the descriptive sense." (R2)

Coney et al also remarked that most terranes seem to possess an oceanic rather than continental character. Also, rocks older than the middle Paleozoic are rare in the terranes of western North America.

Our approach in this Catalog will be to treat terranes simply as phenomena rather than evidence supporting microplate tectonics.

X1. Western North America. By far the most thoroughly studied terranes are those plastered against the western edge of North America, from Alaska to Mexico. Some geologists count over 100 terranes in this 5,000-mile-long jigsaw puzzle. Space limits detailed coverage here. Instead, we present an overview plus descriptions of two specific terranes. The overview is by W. Sullivan and comes from the Smithsonian Magazine.

"A key piece of evidence for terrane theory was the discovery, in certain parcels of western landscape, of tiny fossils known as fusulinids. These belonged to species that some 300 million years ago were native to tropical waters fringing lands that now form southern China and southeast Asia. They bore no close relationship to similar families then living in Texas, Nevada and Kansas. It now appears that much, if not all, of the region west of a zone from Idaho to southern California is formed of bits and pieces of landscape swept up as North America overrode a vast ocean floor, whose western remnant is the Pacific Ocean. The process was at times continuous, like a conveyor belt, at other times halting and sporadic. Mountain ranges and a mosaic of terranes in western North America were the result. Some of that motion continues as the rim



Twenty-nine major terranes are named on this map of Alaska. All told, Alaska is thought to consist of some 50 distinct rock masses. (U.S. Geological Survey, X1)

of California, from San Francisco south, is dragged northwest---chiefly along the San Andreas Fault---and as similar motions occur along the coast of southeast Alaska.

"The evidence shows that some terranes, such as the one forming part of Marin County in California, were created in mid-ocean, far from any source of continental sediment. The Wrangellia terrane that towers as the Wrangell Mountains of Alaska and forms the walls of Hells Canyon on the western border of Idaho seems to have originated more than 300 million years ago as a mid-ocean arc of tropical volcanic islands like Tahiti and its neighbors. The arc's remnants are now scattered along 1,200 miles of the West Coast." (R17)

Salinia. The Salinian terrane is a 500-kilometer-long slice of central California, stretching from just west of San Francisco Bay to a bit south of Bakersfield. R.A. Kerr, a staff writer for Science, wrote the following about Salinia.

"Salinia had for 30 years seemed odd and out of place. Underlain by granite, it is surrounded by a jumble of altered marine rocks called melange...Surrounded by melange and bounded by faults, such as the San Andreas on the northeast, Salinia did not seem to have formed where it is today. By present-day definitions, it would have been called a suspect terrane, as most of the rocks within an average of 500 kilometers of the western coast of North America are now called.

"At first geologists suggested that Salinia had simply slid north 500 kilometers along the San Andreas from where the Pacific plate had sliced it from a similar continental arc. But Duane Champion and Sherman Gromme of the USGS in Menlo Park with Howell argued that Salinia began its travels much farther south. The shallow inclination of the earth's magnetic field recorded in 70-million-year-old Salinian rocks requires that the rocks formed 2500 kilometers to the south, they say, somewhere in the vicinity of present-day Central America. Such a far-traveled block would qualify as an exotic terrane, only a handful of which have been identified paleomagnetically." (R10)

Two blocks of pelagic red limestone near Laytonville, California. These exotic blocks are embedded in the so-called Franciscan melange belt about 200 kilometers north of San Francisco. The exposed portions of the two blocks are measured in tens of meters, making this miniscule in comparison to Salinia. One of the blocks has been overturned. The Laytonville blocks, which might be called "miniterranes", are interesting because they seem to have set distance and speed records as they were carried to northern California.

X2. Eastern North America. In ESR3-X5, we remarked upon the great overthrusts that helped create the Appalachians. All along the East Coast of North America, sheets of crystalline rock have been thrust westward over younger sedimentary rocks for at least 270 kilometers. Only at a few "windows" can we actually see the thrust planes, but seismic surveys by Cocorp (Consortium for Continental Reflection Profiling) have mapped out their full extent. These overthrust sheets fit well with the scenario drawn up by the students of East Coast terranes.

"South Carolina's Robert Hatcher and the Cocorp group propose a scenario for the formation of the Appalachians that seems to account for the geological and tectonic evidence. Their model begins in the late Precambrian era, about 800 million years ago, when a vast rifting occurred in a megacontinent---a rift that may have split Laurentia (Eurasia) as well as Gondwanaland from the North American block. The rifting produced not only large, separating continents, but at least one large continental fragment as well, the Blue Ridge/Inner Piedmont unit. As ocean basins opened among these fragments and continents, the metamorphosed volcanic and sedimentary rocks that are found today in the Blue Ridge were deposited. They were laid down in the ocean basin spreading between proto-North America and the offshore unit destined to return as the Blue Ridge/Piedmont province of what are now the Appalachians.

"The Blue Ridge/Inner Piedmont is thought to have been a part of the North American segment that broke away and later rejoined the continent. The Carolina Slate Belt to the southeast of it, however, appears to be an accreted terrane similar to Wrangellia, Stikinia, and others in the western United States. 'The slate belt is now thought to be part of a separate microcontinent, Avalon, that formed 600 to 700 million years ago,' Hatcher says. Pieces of Avalon may also be found in Rhode Island, Massachusetts, New Brunswick, Newfoundland, Wales, Brittany, northwest Africa, and Spain.

"The tectonic processes that erected the Appalachians suggest a series of collisions with island arcs and continental fragments rather than a single impact with another large continental block. These collisions occurred at intervals roughly 100 million years apart. After each collision, a long period of quiescence ensued, and erosion wore down the mountain chains. Sediments accumulated to great thicknesses in shallow seas east and west of the mountain ranges; those in the east provided new material to be heaped back on proto-North America in the next collision." (R8)

The Carolina Slate Belt. The exotic nature of this huge, elongated structure has been confirmed paleomagnetically and paleontologically.

"Abstract. An assemblage of Middle Cambrian Atlantic faunal province trilobites has been found in the rocks of the Carolina slate belt near Batesburg, South Carolina. Geologic and paleomagnetic data suggest that the Carolina slate belt and the adjacent Charlotte belt constitute an exotic terrane that was accreted to North America in early to middle Paleozoic time." (R9)

Florida as an Exotic Terrane. That part of Florida, too, is exotic territory seems indicated by paleomagnetic and geochronological (rather than paleontological) information.

N.D. Opdyke et al have reported in Geology on the analysis of a core taken at 794-827 meters in Alachua County, northern Florida. The remanent magnetism of these Paleozoic rocks indicated that they were formed at a paleolatitude of 49°, whereas reconstructions of early Paleozoic North America place Florida at about 28°. Further, radiometric dating of the rock yielded dates ranging from 1650 to 1800 million years ago. North America has no known rocks of this antiquity. "These two new lines of geologic data provide strong evidence confirming previous suggestions that Florida was part of Gondwana during the early Paleozoic and that its current configuration is that of an exotic terrane sutured to North America during the fragmentation of Pangea." (R25)

X3. The interior of North America. Many geologists are now convinced that the edges of North America consist of belts of many welded terranes several hundred kilometers wide. But what is at the core of North America? Is it really that ancient, stable land mass (or "craton") that geologists have assumed for decades? Apparently not. North America's core seems to be a collage of four or five smaller cratons, all older than 2.5 billion years. They were probably united about 2 billion years ago. Before this time, these cratons were essentially minicontinents drifting over the surface of the globe under the influence of the same forces that cause today's tectonic plates to wander. The minicontinents were of various sizes: one was smaller than Texas, another about one-fifth the size of modern North America. While a few of these primitive cratons were welded together by collision, others are separated by belts of deformed rock called "orogens". Within the orogens are rocks resembling bits of ocean crust ("ophiolites") as well as island-arc material. Geologists think that the orogens were simply swept up by the cratons and crushed between them. The nature of North America's core convinces many scientists that the forces driving plate tectonics were active long before the terranes were plastered against the continent's edges beginning some 200 million years ago. Therefore, whatever the mechanism causing continental drift, we know it was active early in the earth's evolution. This fact may help in unravelling the history of the earth's core and mantle. (R15, R20)

X4. Asia. Terrane mapping has not progressed as far in Asia as it has in North America. Even so, geologists familiar with this vast continent believe that Asia "actually results from the juxtaposition of many blocks of diverse origin." (R17)

By 1983, terrane enthusiasts had split the far northeastern part of the Soviet Union into 32 terranes, China and Mongolia into 49, and the Philippines into 9. (R10)

So far, we have collected specifics on only one Asian terrane.

The Tokoro Belt. "New paleomagnetic, paleontologic and stratigraphic data from the Tokoro Belt of Hokkaido, Japan, suggest an equatorial origin in early Cretaceous times. The Tokoro Belt consists of basic hyaloclastites and pillow lava associated with radiolarian chert and limestone of the Nikoro Group, unconformably overlain by Campanian turbidites of the Saroma Group. The Nikoro Group lacks terrigenous detritus and, while structurely complex, is coherent in the sense that a melange matrix is not present. The limestone includes coralline shallow water, oolitic and pelagic facies." (R24)

X5. South America. Terrane data are even scarcer from this continent.

Northwestern Peru. "A paleomagnetic study of over 250 cores from 26 sites sampled in Early to Late Cretaceous and Paleogene volcanic, plutonic and sedimentary formations of the Lancones basin in the Piura province of northern Peru, indicates that most of these lithologies carry a stable primary remanent magnetization whose direction is significantly different from that of coeval formations of stable South America....When considered together with previous geological studies, these data are consistent with the hypothesis of accretion of an Amotape-Tahuin continental terrane to the Peruvian margin in Neocomian times. The accretion was followed by in situ rotation, suggesting a dextral shear regime.

These results indicate that the geodynamical evolution of northern Peru is more closely related to the processes observed in Ecuador than those classically assumed for the Central Andes of Peru." (R28)

X6. Europe. So far, our files contain only two examples of possible terranes from the European continent: (1) "...the fault-bounded Caledonian terrains [sic] ---which now compose the Grampian Mountains, the Southern Uplands, the Lake District, Wales and part of Ireland." (R24); and (2) A microplate called Adria in northern Italy, which is thought to have been once been part of Africa. (R29)

Although no specific terranes have been mapped out, I. Haydoutov has described Precambrian ophiolites and Cambrian island-arc deposits from the South-Carpathian-Balkan region. (R30) Note the similarity with the orogens in the interior of North America. (X3)

X7. Other continents. No data have been found for terranes (if any) in Australia, Africa, or Antarctica.

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ESR10 Long Belts of Igneous and Metamorphic Rocks

Description. Linear structures of igneous and metamorphic rocks that stretch for thousands of miles and, in some instances, girdle the earth.

Data Evaluation. Scientific observations of the anorthosite belts (X1), the Andesite Line (X2), and the greenstone belts (X3) are substantial and of good quality. On the other hand, the other belt-like structures (X4 and X5) are barely mentioned. Rating: 2.

Anomaly Evaluation. The belts of rock described below are so extensive that their origins almost certainly required the actions of planet-wide forces. The mechanisms proposed to explain the belts can be divided into four groups:

1. Internal planetary forces, such as heat release and vertical tectonic forces
2. Horizontal forces produced by tectonic-plate motions (which, of course, may in turn be generated internally)
3. Tidal forces created by the close approach of the moon
4. Forces produced by the impacts of meteorites/asteroids.

Historically, the scientific acceptability of these mechanisms seems to have been in the order that they are listed. Today, only phenomena explained in terms of (3) and (4) might be considered mildly anomalous. Although all four mechanisms have been employed at one time or another to explain the belt phenomena described below, none of the phenomena has a widely accepted explanation. The challenges to geological paradigms posed by belt structures relate primarily to the real nature of the earth's early history. With today's wide acceptance of catastrophic events in the interpretation of earth history, belt phenomena are not especially anomalous. Rating: 2.

Possible Explanations. See above.

Similar and Related Phenomena. Large terrestrial craters (ETC); anomalies that challenge the theory of plate tectonics (ETL); near-global unconformities (ESR4); exotic terranes (ESR9).

Examples

X1. The anorthosite belts. Anorthosite is a variety of rock consisting of over 90% plagioclase feldspar. Although anorthosite does occur in some ancient layered igneous and metamorphic rocks, our focus here is on the anorthosite plutons (igneous intrusions) that occur in two planet-circling belts. The anorthosite comprising these plutons is nearly constant in composition wherever found. Furthermore, the radiometric ages all cluster around 1,300-1,400 million years, with a range of 1,100-1,700 million years. The common age and chemical composition combined with the occurrence of the anorthosites in two belts; one in the Northern Hemisphere, the other in the Southern; suggest some sort of cataclysmic event far back in the earth's history. Anorthosite is not associated with ordinary volcanic emissions, so the supposed event may have reached deep down into the earth's crust. (R2, R6)

An impressive array of anorthosite massifs forms the Adirondacks of New York. (Some immense crystals of anorthosites can be found in North America ---6 feet in diameter and 18 feet long, although most are measured in inches.) From the Adirondacks, the Northern Hemisphere belt runs east through Greenland, Scotland, Norway, Poland, and the Ukraine. In the other direction, one finds anorthosite plutons in Virginia, Wyoming, Nebraska, Idaho, Montana, and even California. The belt is not so well-defined to the south and west of the Adirondacks; and there may be two sepa-

(Above) The southern anorthosite belt as it existed before the onset of continental drift about 200 million years ago. (Below) Anorthosite occurrences in the northern hemisphere. (X1)

rate branches. (R5) The Southern Hemisphere belt has been identified in Brazil, Angola, Tanzania, Madagascar, India, Australia, and Antarctica. When the two belts are plotted on pre-drift maps of the continents, symmetry and order are much more obvious. (R2)

What sort of planet-wide event could account for such symmetrical, belt-like structures? N. Herz has championed the birth of the earth-moon system as the probable cause. Some 1,300 million years ago, he theorizes, the proximity of the moon to the earth resulted in intense tidal action and heat production deep within the earth. The result was the eruption of the two anorthosite belts. (R2) Other scientists have proposed the impact of a giant meteoroid/asteroid. Still another possibility is an internal event, such as a widespread, heat-releasing chemical phase change. It is all speculation at present.

See ESD3-X3, where the close approach of the moon is blamed for the deposition of the tillite conglomerates circa 700-1,000 million years ago.

X2. <u>The Andesite Line</u>. At the outset, we require a definition of "andesite". For this and other background information, we rely on A.J. Eardley.

"Andesite is a volcanic rock of higher silica content than its neighbor and common associate, basalt. Basalt is believed to come directly from the subcrust or sima, which is also believed to be basaltic in composition. Andesite, on the other hand comes from a molten rock which is either a basalt contaminated with material from the sial or has been produced entirely by the melting of the lower part of the sial. Andesite, therefore, is believed to mark continental conditions and perhaps, more specifically, mountain belts whose roots are melting." (R9)

It is significant that andesite does not occur at random. L. King has set forth the problem of the so-called Andesite Line.

"Petrologists early remarked the abundance of rocks of the andesite clan about the borders of the Pacific, associated in many instances with mountain ranges and island festoons. Andesites continue also for some hundreds of miles into the continents, and they occur locally in small quantity upon certain of the oceanic islands, but the distribution is clearly zonal, girdling the Pacific Basin. This zone is known as the Andesite Line, and it is petrographically and tectonically of the highest significance. It marks essentially the boundary between the sialic masses of the continents and their outliers with the basaltic floor of the ocean basin. As such it constitutes one of the fundamental geological boundaries of the earth." (R1)

"The Andesite Line separates the andesitic volcanoes of the western Pacific island arcs from those of the basaltic Hawaiian Islands, and from the basaltic Midway, Wake, Marshall, Gilbert, Ellice, Samoa, and Caroline islands. Within the andesite province are the Bismarck, Solomon, New Hebrides, New Caledonia, Fiji, Tonga, Kermadee, Chatham, and Aukland islands and New Zealand." (R9)

Elsewhere on the planet, the distinction between basaltic and andesitic regions is not so sharp. Other andesite regions include patches of southern Europe, the Middle East, and the islands of the eastern Caribbean. (R3) One can only wonder why the Andesite Line girdles only the Pacific Basin. Is there something different about the Pacific Basin?

As a matter of fact, several scientists have ventured that the Pacific Basin just might be the scar left from the impact of either a giant meteorite or the fission of the moon from the earth. See ETC2-X1.

X3. The greenstone belts. Greenstone belts are elongated patches of dark-green, metamorphosed, mafic (ferro-magnesian), igneous rocks. Greenstone belts are rather common in Precambrian systems. Chlorite amphiboles, epidote, and serpentine contribute to the greenish hues. The debate over the origin of the greenstone belts has been long and is still unresolved. Why are they arranged in linear bodies? What created them? An early explanation was that they erupted through thin-bottomed, linear troughs in the crust, but later emphasis shifted to plate-tectonic explanations, as related by R.B. Hargraves below.

"Considering the greenstone belts alone, Anhaeusser et al. favored their formation in 'downwarps or fault-bounded troughs on an unstable, thin, primitive sialic crust.' Windley suggested an analogy with mid-ocean ridges. However, Goodwin, Anhaeusser, and others have been particularly impressed by the similarities between greenstone piles and contemporary island arcs, and favor a similar 'subduction' mechanism for the formation of both. More recently, plate tectonic analogies have been drawn between greenstone belts and the deposits that accumulate in marginal basins behind arcs." (R7)

Reinforcing the thought that the greenstone belts might be related to the orogens mentioned in ESR9-X3, has been the discovery of remnants of oceanic crust (ophiolites) within the belts. R.A. Kerr carries along this theme below.

"While the debate over possible slivers of ocean crust caught in greenstone belts continues, new fieldwork is transforming views of the greenstone belts themselves. A plate tectonic origin for them is gaining the upper hand. No longer do they seem to be 20-kilometer-thick piles of lava that welled up onto continents through stretched and thinned crust, only to sink later under their own weight. Instead, geologists are increasingly viewing a greenstone belt as a jumble of volcanic lavas, sediments, and injected magma. That is exactly what remains when continents collide and squeeze a volcanic arc like the Aleutian Islands or Japan between them. Scraps of ocean crust containing evidence of sea-floor spreading would thus be just one bit of the evidence that horizontal motion of plates, rather than simple ups and downs of the crust, dominated the Archean as it does the present." (R11) This shift from vertical to horizontal mechanisms to account for the earth's features has been seen many times in Chapter ESR---in ESR9, in particular. (WRC)

In 1985, a new factor complicated the conventional explanations of the greenstone belts.

"Donald Lowe and Gary Byerly (Louisiana State University) reported the discovery of extensive deposits of spherule-bearing rocks in the 3.3 to 3.5 billion-year-old greenstone belts of South Africa and Western Australia that strongly resemble the interiors of chondritic meteorites. The spherules are largely altered compositionally, but retain original textures that indicate solidification and partial quench crystallization of liquid silicate droplets. While volcanic origins are not ruled out, their origin as impact shock melts is favored." (R10)

In the Barberton Greenstone Belt (South Africa), the spherule layer is thought, by Lowe and Byerly, to be a half-meter thick in some places. This spherule layer can be traced over "hundreds and possibly thousands of square kilometers." Lowe ventured, "It's almost inconceivable that the grains could be carried this far during volcanic processes." (R12)

Later research by Lowe and Byerly brought forth additional facts: the spherules measure between 0.1 and 4 millimeters across and are massed in layers between 10 centimeters and 1 meter thick. They seem to have been condensed from clouds of vapor produced by the impacts of meteorites/asteroids. (R13) The implication is that the force of impact somehow created the greenstone belts themselves, although the mechanism and scenario are obscure.

X4. A red granite-rhyolite belt in North America. An enigmatic type of rock, combining granite and rhyolite, stretches in a broad belt several thousand miles long from Labrador to southern California. "Enigmatic" is an apt adjective because rhyolite is usually formed when magma erupts onto the surface and cools quickly, while granite develops from magma that is cooled slowly deep underground. Chemically, rhyolite and granite are essentially identical, only their texture differs. Their admixture in a long belt is, therefore, puzzling.

The granite-rhyolite belt reaches the surface in only a few places---Missouri, Oklahoma, and a few other locales---but drill holes across the continent commonly strike these rocks 1 or 2 kilometers down. Their total volume must be immense. The age of the belt is put at 1.3-1.6 billion years. (R15)

Granites and rhyolites often form where tectonic plates either collide or pull apart. Just how the North American granite-rhyolite belt relates to the orogens and primitive cratons thought to make up the continent is unknown. (See X3.)

X5. The Dupal anomaly; two belts displaying anomalous isotope ratios. This interesting phenomenon has been sketched by P Castillo.

"[B.] Dupre and [C.J.] Allegre recognized that lavas from oceanic islands in the South Atlantic and Indian Ocean have high $^{87}Sr/^{86}Sr$ ratios ($\sim$ 0.7035) and anomalously high $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios for a given $^{206}Pb/^{204}Pb$ ratio compared with North Atlantic and East Pacific Islands. [S.R.] Hart termed this isotope signature and its geographical distribution on the ocean floor the 'Dupal anomaly' and showed that although the strongest maximum of the anomaly stretches from the Indian Ocean to the South Atlantic Ocean, a second maximum with an only slightly high $^{207}Pb/^{204}Pb$ ratio exists in the southern Central Pacific Ocean. Hart also suggested that the two maxima are connected, forming a globe-circling belt centered on latitude 30°S. The two Dupal anomaly maxima appear to be located above the minima of the two large-scale regions of low seismic velocity (LVRs) in the lower mantle, as well as above concentrations of the majority of active hotspots." Castillo remarks further that these correlations raise the likelihood that large-scale features of the lower mantle may produce geochemical signatures on the earth's surface. (R14)

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EZ THE GEOMAGNETIC FIELD AND PALEOMAGNETISM

Key to Categories

EZC MINOR PERTURBATIONS OF THE GEOMAGNETIC FIELD
EZF CONFIGURATION ANOMALIES AND SECULAR VARIATIONS OF THE GEOMAGNETIC FIELD
EZP PALEOMAGNETISM

The earth's magnetic field varies from place to place geographically. It varies in intensity and direction on scales of seconds to years to millennia. Its configuration is always changing, too, in hard-to-fathom ways. Although predominately resembling the field of a bar magnet, a substantial portion (about 10%) of the geomagnetic field is nondipolar. This dipolar portion waxes and wanes here and there over the surface of the planet as well as in the crust and mantle beneath our feet. Obviously, we have at hand a most complex phenomenon.

Fortunately, we have excellent instruments for measuring the vicissitudes of the present geomagnetic field. Also, historical records of field measurements go back almost 400 years. In paleomagnetism, we have a way of estimating what the geomagnetic field has looked like through geological time. Looking far backward in time is possible because some rocks and sediments recorded the prevailing magnetic field when they solidified or piled up on lake and ocean floors. The volume of magnetic data accumulated by ground survey parties, by deep-sea drilling, and by satellite magnetometers is impressive. Residing within this data base are many perplexities and outright anomalies.

Earth scientists currently visualize a solid inner core at the earth's center. This is surrounded by a fluid outer core which, through dynamo action, generates the geomagnetic field. As a matter of fact, no physically reasonable alternative to the geodynamo exists at the present time. Yet, the geodynamo theory has trouble explaining the hundreds of polarity reversals that permeate the geological record. The precise causes of secular variations of the field and the large regional anomalies are also difficult to accommodate with the geodynamo theory. In short, the geodynamo theory is far from perfect, but it is the only viable one.

Paleomagnetism, like the geodynamo theory, is well-accepted by earth science. But its methodology is suspect---at least to some outsiders and a very few insiders. In addition, this chapter's section on paleomagnetism (EZP) details several anomalies and inconsistencies. Paleomagnetism is part of the foundation supporting plate tectonics, and any cracks in its structure are scientifically serious.

EZC MINOR PERTURBATIONS OF THE GEOMAGNETIC FIELD

Key to Phenomena

EZC0 Introduction

Superimposed upon the general geomagnetic field, which itself displays many anomalies (EZF), are numerous minor perturbations, most of which are probably associated with geological structures. It should be mentioned at the beginning that any deviation of the geomagnetic field from the idealized geomagnetic field established by the geophysicists is termed an "anomaly", even if the source of the perturbation is well-understood. In contrast, "anomalies" in this Catalog are those observations which challenge prevailing paradigms. Thus, the door is left open for for a seemingly self-contradictory entity: the "anomalous magnetic anomaly"!

Most of the anomalous magnetic anomalies are simply small deviations of the geomagnetic field arising from unrecognized, local ore bodies or other concealed geological structures. The phenomena recorded in EZC1, EZC2, EZC4, and EZC5 fall into this category and are, therefore, not especially anomalous, according to the definition of the word, as used in this Catalog.

Only in EZC3 do we encounter more profound anomalous magnetic anomalies. Here are found the several challenges to the theories of seafloor spreading and plate tectonics, which are so dependent upon magnetic profiles recorded over the mid-ocean ridges. The plate tectonics paradigm is so strongly entrenched today that the very existence of anomalous magnetic anomalies is usually passionately denied. For this reason, EZC3 is the most important in this chapter.

EZC1 Local Compass Anomalies

Description. Localized deviations of the compass needle of 10° or more from the values expected for the overall region. Many of these magnetic anomalies exert their influences over only a few miles or even only a few hundred feet.

Data Evaluation. The observations recorded below came primarily from ships' logs. This is to be expected because navigators must watch their compasses carefully. The few terrestrial observations are rather old. No surveys or general studies of this phenomenon have been located as yet. Rating: 2.

Anomaly Evaluation. Small deviations of the compass needle are quite common and are usually attributed to nearby ore bodies and other geological phenomena. Even though the examples presented below are very large, there is no reason to suppose that the same explanations do not hold. Consequently, only curiosity value can be claimed here. Rating: 3.

Possible Explanations. Ore bodies; earth currents; small areas magnetized by lightning strikes.

Similar and Related Phenomena. Magnetized geological features (EZC2); regional magnetic anomalies (EZC4).

Examples

X1. Off northwestern Australia, near Bezout Island.

September 1885. "In September 1885, on board H.M. surveying-vessel Meda, when passing Bezout Island near Cossack, North-West Australia, a steady deflection of her compass of 30° was observed, Whilst the ship was running over half a mile in a north-north-west direction and in a depth of eight fathoms of water. This remarkable result has since been exceeded by observations made in H.M. surveying-vessel Penguin on November 6, 1890.

"On this occasion, the Penguin, being 2 miles N. 79° E. from Bezout Island, a deflection of 22° was observed in her compass. The ship was immediately anchored, and some hours of the next day were spent in drifting backwards and forwards near that position, and the following results were obtained.

"On Bezout Island the absolute values of the variation and dip were normal, the dip being 50° 1'.7 S. But at a position N. 70½ E, distant 2.14 miles from that on Bezout Island, the observed dip on board was 83° S, with a very small deflection of the compass. This may be considered the central point of the disturbing force. At 900 feet to the westward of this the dip was normal, and it decreased rapidly as the centre was quitted in any direction. At about 100 feet south of the centre of disturbance, the compass was deflected 55°. This was the largest deflection observed, but the compass was disturbed over an area of about a square mile. The general depth of water in this area was nine fathoms, and the quality of the bottom quartz sand.

"The observations of the magnetic elements at Cossack and the neighbourhood showed little or no disturbance from local magnetic effects. It is therefore evident from the remarkable results now related, which have been derived from observations of undoubted accuracy, that the deflections of the compass in the Meda and Penguin were due to magnetic minerals at the bottom of the sea adjacent to the ship." (R1; R2)

Almost a half century later, similar observations were made at the same locale from the S.S. Gascoyne.

"On arriving from---and departing for---southerly ports at Cossack, we almost invariably pass Bezout Island at three miles distant, and on passing over a spot with the south end of the Island bearing about S. 60° W. the compass card is suddenly deflected between 55 and 60 degrees in an anti-clockwise direction. The card remains at this position for at least five minutes as a rule and then gradually readjusts itself, showing that the patch of magnetic sand (presumably) on the sea floor is fairly extensive.

"We visit Cossack on our intinerary regularly every six weeks, and the phenomenon is observed unfailingly on every occasion.

"I have never heard of such a large deflection anywhere else in the world, though possibly there are spots with as large---or a larger---disturbing influence. I should like to hear of them. (R8)

X2. Central Russia.

"The following curious statement is an item of interesting news, if puzzling:--- The results of the investigations made by a French savant and Russian scientists into the extraordinary delection of the magnetic needle over an immense area of Central Russia, show that the greatest aberrations are found in the province of Kursk, the capital town of which is some 600 miles almost due south of Moscow. In the northern part of the province, near Tim, the needle deflects 20°; further south, in the district of Staroi Oskol, up to 30°; while in the south-east of the province, about 150 miles south of Tim, the deflection is over 96°, the needle standing almost perpendicular, and pointing east and west, instead of north and south." (R3)

The preceding item from the English Mechanic was amplified in the Geographical Journal.

"At a meeting of the Academy of Sciences of Paris on May 9, M. Mascart announced that Prof. Leist of Moscow had discovered a curious magnetic disturbance at Kochetovka, in the government of Kursk. At this place there was a point at which the horizontal magnetic needle pointed in any direction, and the dipping-needle was vertical. The phenomenon was so local that at a distance of 70 feet from the centre of vertical dip the declination decreases by 1°." (R4)

X3. The Hebrides.

"In the course of a recent survey in the Hebrides, Captain A. Mostyn Field, in H.M.S. Research found and examined an area in the entrance of East Loch Roag, Lewis, where there is considerable local magnetic disturbance...The maximum deviation is 11° W. The remarkable point in this instance is not only the magnitude of the disturbing force, the depth of water and therefore the distance of the compass from the bottom being 100 feet, but that the north point of the needle is repelled from the apparent line of magnetic disturbance, and not attracted towards it as is usually the case in northern latitudes." (R5)

X4. Near Juneau, Alaska. The following item consists of the caption for a photograph showing a tent erected beside the water, with an observer kneeling at the end of a long boom. (Figure 2 from R6.)

"A local magnetic north pole at Treadwell Point, near Juneau, Alaska, as disclosed by L.A. Bauer's observations in 1900 and 1907. [In the center of the tent the dipping needle stood vertical, with the north end down, and the compass reversed its direction when carried from one side of the tent to the other. Ships' compasses, a mile away, in Gastineaux Channel, are deflected about 11°.]" (R6)

X5. Spencer Gulf, South Australia.

December 4, 1927. From the Meteorological Report of the S.S. Clan Macnaughton. "...at 0025 when off Lipari Reef Light (Spencer Gulf) the compass was found to be strongly affected by some local disturbance and was some 9 degrees in error above what was allowed. As soon as the light was passed this disturbance ceased to be felt to any marked degree. Allowed variation: 4° 15' E., deviation 2° 45' E." (R7)

August 23, 1965. While the S.S. Neleus was proceeding through Spencer Gulf, compass disturbances from 15° E to 12° W were experienced. The disturbances were obtained by comparing magnetic and gyro compasses. "The initial deflection of 12° took about one min to complete, but the second deflection of 27° took only about 20 sec and when it returned to normal it did so at the same speed. The compass returned to its correct heading between each disturbance; only between the first two did it cross straight over. A note on the chart draws attention to magnetic disturbances, especially towards the western side of the Gulf." (R15)

X6. East Indies, near Tambora Volcano.

June 3, 1929. From the Meteorological Log of the S.S. Clan Macwhirter. "At first the deflection of the needle was very slow, so slow that the quartermaster began to follow his course and it was not until the officer noticed the land drawing ahead that any action was taken.

"The ship was brought to her course again, approximately by sighting the wake astern

"The needle was deflected 6 points (i.e., from North to E.N.E., true North being indicated by W.N.W.) and the card oscillated about a point (Ship's head by compass N.N.E.) for about 2 minutes."

"The disturbance lasted about four minutes, then the compass swung back very rapidly when clear of the field." (R9)

X7. Off Western Australia.

October 14, 1931. From the Meteorological Log of the S.S. Australia. "...while approaching Fremantle (04-08 Watch) from the westward abnormal magnetic disturbance was experienced with Standard and Steering compasses swinging about 12° each side of course. Average period of vibration was about 10-12 seconds. Vessel was about two miles north of Rottnest Island." (R10)

August 22, 1934. Report from the S.S. Querimba. "Whilst in the vicinity of Escape Island, on August 22nd, 1934, between the hours of 10.00 a.m. and 11.30 a.m. and steering S. 8° E. (T), I experienced a most abnormal magnetic disturbance. All my compasses were rendered useless during this period, and the vessel had to be steered approximately by the lay of the land. At 11.10 a.m. Escape Island was abeam 8 miles. At 11.30 a.m. when this island was bearing N. 61° E., 9 miles (T), the standard compass and bridge compass gradually became normal again, but my steering compass card still remained quite useless, and had to be changed for the time being.

"I am aware that parts of the N.W. and West coast of Australia are subject to exercising local magnetic attraction on one's compasses if one passes close to the land at these places of influence; but have never before experienced such a very pronounced disturbance to the compasses; and never at all in this particular vicinity, although having passed off Escape Island many times at 9½ to 12 miles distance. I am not definitely sure if this disturbance was caused by some magnetic influence on Escape Island, or if I happened to pass directly over a thin line on the sea-bed, composed of some magnetic substance running approximately North and South, between say Latitude 30° 11' S. and 30° 25' S. and Longitude 114° 49' E., and 114° 51' E. I am rather inclined to the latter view, as my compasses behaved much the same as I have experienced them to do, if one passes over an iron wreck in shoal water; only in this instance I was in about 27 fathoms of water, and the influence lasted fully 1½ hour." (R11)

X8. Soviet Arctic.

"In 1937, a Soviet scientist, B. Weinberg, advanced the hypothesis of two magnetic north poles, and in 1940 predicted that the second should be in the Sedov region of the arctic. Now a Russian geographer, M. Ostrekin, concludes that 'the existence of two poles in the Arctic is no more a speculation, but a certainty,' according to the Indian journal Science and Culture.

"In 1945, a British expedition flying over the Sverdrup Islands noted compass deviations as great as 89 degrees, and the magnetic pole was assumed at have a new location. Science and Culture comments on the importance of the Soviet findings, but cautions against any final decision until an international expedition has studied the problem." (R14)

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EZC2 Magnetized Geological Features

Description. Small-scale geological features, such as mountain peaks and lakes, that are the sources of magnetic anomalies; that is, they produce compass and magnetometer readings that do not conform to the magnetic environment of the region.

Data Evaluation. Although the magnetization of rocky peaks and ridges is purportedly a common phenomenon, few reports on this subject seem to have found their ways into the scientific literature. No surveys or general studies have been found at all. Only a single study of the magnetic changes due to the filling of an artificial lake has been located. Rating: 3.

Anomaly Evaluation. The physical mechanisms leading to the magnetization of geological features are lightning strikes and the piezomagnetic effect. In the former, the powerful earth currents accompanying lightning strikes are believed to induce magnetism in the nearby rocks; in the latter, it is the pressure of a newly filled lake on piezomagnetic materials that changes the ambient magnetic field. These explanations are commonly accepted, even though no one seems to have investigated the phenomena in depth. Indeed, skeptical though we are about simplistic explanations, we see no reason to characterize these phenomena as anomalous. Rating: 4.

Possible Explanations. As stated above.

Similar and Related Phenomena. Small-scale magnetic anomalies (ESP7); spalled and shattered rocks attributed to lightning strikes (ESM1-X5).

Examples

X1. Rock pinnacles and other exposed points. Lightning often strikes specific peaks and exposed geological features repeatedly. It is not surprising to find the compass needle deflected in such regions.

Great Britain. Recollections of E. Hill concerning compass deflections in Great Britain.

"Four years ago, on a visit to the Lizard, accident drew attention to a strong influence on the compass exhibited by a crag on the moors near Kynance. I have taken the opportunity on a visit this year to ascertain whether that were a solitary case. I find that such influence, though not general, is by no means uncommon. Most of the rocks in which it was observed were serpentine; it occurred also in hornblende schist; there were no sufficient opportunities of testing the other rocks of the district. The influence was exhibited only in rather prominent crags, but among them often in lower adjacent blocks, as well as in the absolute summits. At a few yards' distance it was always imperceptible.

"I saw no traces in any case of the crag having been struck by lightning. This was the only point to which I gave attention; but it would be natural also to inquire if all kinds of rock can possess the property, if wet or weather affects it, and if it be temporary or permanent.

"I used a common pocket compass, taking the bearings of some distant object, first a few feet off, then in four surrounding positions as near as the compass could be held to the stone I was testing. The effects varied from no deviation to slight, to cases where the needle swung completely around while still a foot or two away. Among the strongest noted were some crags north of Kynance Cove, and some on a headland about a quarter of a mile south of Coverack, both consisting of serpentine." (R1; R2)

Switzerland. "It is well known that the Riffelhorn powerfully affects the compass, and the like has been observed on other peaks in Switzerland." (R1)

United States. In 1963, A.L. Agron reported the discovery of a magnetized sandstone ridge near Newport, Rhode Island. The sandstone contains numerous thin bands of magnetite. The compass needle deviated 5°-10° when brought near the bands, but within a one-square-foot area the deviation was about 180°. This highly magnetic spot was attributed to the effects of lightning. (R3)

Undoubtedly, many additional observations of a similar nature have been recorded. Our intent here is simply to provide typical examples of this interesting but nonanomalous phenomenon. (WRC)

X2. Magnetic anomalies at man-made lakes. Large artificial lakes impose great stress on the underlying rocks. In at least one well-instrumented survey, a marked piezomagnetic effect was noted as the lake filled up.

Australia. In 1972, a new dam emplaced at Talbingo, in Australia's Snowy Mountains, created a 730,000-acre lake with a maximum depth of 480 feet. Magnetometer readings taken at 15 survey points before and after filling showed changes ranging from +2.2 to -8.0 gammas. (R4)

X3. Buried impact structures. Bull's-eye patterns of gravity anomalies are thought to indicate the presence of buried impact structures. Such a gravity pattern has been found recently in North America. (ECG1-X4) Some geophysicists are of the opinion that large asteroid/comet impacts may also create bull's-eye patterns of magnetic anomalies. A specific possibility has been reported.

Mexico. A pattern of concentric magnetic rings has been discovered on the Yucatan Peninsula. The inner ring is 60 kilometers across; the second, 180 kilometers. The rocks creating the pattern are thought to be about 1100 feet down. Since these rocks would probably be late Cretaceous in age, this potential impact feature may be the eagerly sought scar of the aseroid/comet impact that some think wiped out the dinosaurs at the Cretaceous-Tertiary Boundary about 65 million years ago. (R5)

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R5. "Possible Yucatan Impact Basin," Sky and Telescope, 63:249, 1982. (X3)

EZC3 Anomalies of Oceanic Magnetic Anomalies

Description. Magnetic profiles obtained by ship-towed magnetometers that challenge the theory of plate tectonics and, in particular, the hypothesis of sea-floor spreading. More specifically:

X1. Asymmetry of the magnetic stripes
X2. The decrease of magnetic-anomaly amplitude with distance
X3. Fine structure of the magnetic profiles
X4. The dating of sea-floor magnetic anomalies
X5. Correlation and continuity of the magnetic stripes
X6. Anomalies in the North Pacific
X7. Anomalies in the Western Pacific
X8. Anomalies in the Atlantic Ocean
X9. Sea-floor spreading and the expanding earth hypothesis

Data Evaluation. An impressive reservoir of scientific references is available for the subject phenomena, as befits research on one of the more important paradigms of geology/geophysics. The great majority of these papers does not contradict the paradigm. The reports that do---and which form the basis of this chapter---are few in number, although often of high quality and prepared by respected scientists. Rating: 2.

Anomaly Evaluation. Data that are not compatible with plate tectonics and sea-floor spreading are highly anomalous. Rating: 1.

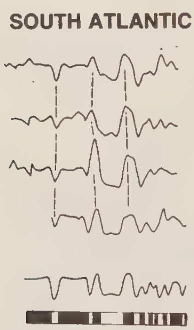
Possible Explanations. The purported normal- and reversed-polarity magnetic stripes parallel to the mid-ocean ridges might: (1) be due only to fluctuations (not reversals) of the dipole field; and (2) be actually expressions of deep crustal structure completely unrelated to continental drift.

Similar and Related Phenomena. Terrestrial magnetic anomalies (EZC4); topographical phenomena associated with continental drift (ETL); paleomagnetic anomalies (EZP).

Examples

X0. Baseline theory. Sea-floor spreading is an integral concept in plate tectonics. Therefore, any facts casting doubts upon the reality of sea-floor spreading are anomalous. In the context of magnetic anomalies, critics of plate tectonics have garnered a rather long list of potential problems for the hypothesis of sea-floor spreading, as delineated below in X1-X9.

First, though, a sketch of the sea-floor spreading model and its nonanomalous magnetic anomalies. (In geomagnetism, <u>any</u> departure from the "normal" geomagnetic field is termed an "anomaly".) As fluid basalt wells up along the mid-ocean ridges, it spreads horizontally and solidifies. As it cools, it is magnetized by the earth's magnetic field. This remanent magnetic field can, according to the model, be detected by magnetometers towed by ships on the ocean's surface. If the geomagnetic field reverses repeatedly during the formation of the sheets of basalt spreading out at right angles to the axes of the mid-ocean ridges, the ship-towed magnetometers will detect increases and decreases in the geomagnetic field due to the normal and reversed strips of magnetized basalt below. The magnetic record will look something like that in the accompanying illustration. The stripes of normal and reversed basalt shown in the sketch are normally <u>inferred</u> and not measured by actual sampling of the basalt.



Typical magnetic anomaly profiles projected perpendicular to the trend of the lineations. Normal and reversed magnetic periods are indicated on the bar. (X0)

The stripes of magnetized basalt parallel the axes of the mid-ocean ridges. It is assumed that they can be dated by correlating their polarity patterns with those of radiometrically dated terrestrial lava flows. These long, parallel stripes of normal and reversed basalt can be correlated, named, and dated in all of the earth's oceans. These neat stripes, nicely correlated on a planet-wide basis, provide strong, philosophically satisfying

Typical magnetic stripes recorded along the Mid-Atlantic Ridge. (X0)

support for sea-floor spreading and, in turn, plate tectonics.

In what follows, it will be noted that opposition to sea-floor spreading comes from three sources: (1) Scientists who are disenchanted with plate tectonics in general and who have amassed many factual objections; (2) Scientific creationists who favor a "young-earth" model grossly at odds with the theories of sea-floor spreading and plate tectonics; and (3) Some followers of I. Velikovsky who maintain that the magnetic anomalies athwart the mid-ocean ridges actually result from strain patterns induced by recent catastrophism.

X1. <u>Asymmetry of the magnetic stripes</u>. In popular articles and textbooks, the normal and reversed magnetic stripes on either side of the mid-ocean ridge axes are usually portrayed as nicely symmetrical. Some critics of plate tectonics consider this idealization to be misleading. The quotation below from A.A. and H.A. Meyerhoff will illustrate this position.

[The accompanying figure]"shows typical examples of very symmetrical magnetic profiles that are referred to repeatedly in continental drift literature. Despite the vague symmetry, the profiles are deceiving beause (1) they are from only a narrow central zone across the mid-ocean ridge and (2) they are atypical of midocean ridge profiles as a whole. Even where good symmetry is found, the fact is rarely mentioned that the farther the profile is carried from the ridge axis the greater the asymmetry becomes. Another fact rarely mentioned is that symmetry commonly is so poor that neither on-strike nor reverse correlations are possible." (R7)

Lack of symmetry, in the opinion of the compiler, does not seem to be a very strong complaint against the sea-floor spreading hypothesis. The upwelling of magma from the mid-ocean ridges would probably be a rather messy business. Also, one plate could very well be moving away from the axis faster than the other. Nevertheless, the Meyerhoffs imply that the sea-floor spreading theory requires more symmetry than is actually present in typical locations. Symmetry or lack of it can be subjective. (WRC)

X2. The decrease of magnetic-anomaly amplitude with distance. There are, as P.J. Smith relates below, reasons why some reduction in anomaly strength might occur as distance from the mid-ocean ridge increases, but are they adequate to explain what is actually observed?

"When marine magnetic anomalies were first analysed in detail in the early 1960s, it immediately became clear that their amplitudes decrease with distance from the corresponding oceanic ridge. Possible explanations for this phenomenon were not long in coming. For example, the magnetic constituents of the oceanic lithosphere newly formed along the ridge axes may change chemically with time, giving rise to a gradual decrease of magnetisation. Another suggestion was that older igneous crust would be overlain by a thicker deposit of sediment; so the anomalies as measured at the ocean surface would be attenuated with respect to those observed above younger crust with less accumulated sediment.

"But although these and some other processes, acting either individually or together, could possibly explain a gradual decrease in anomaly amplitude, they were apparently insufficient (at least in the form originally envisioned) to account for the precise form of decrease actually observed. For there is usually a particularly large reduction in amplitude immediately beyond the central anomaly followed by a much more gradual decrease outwards towards the continental margins. In the case of slow-spreading ridges (~ 30 mm yr^{-1} half-rate), for example, the central anomaly amplitude can be at least twice as high as those of near neighbours, although for faster-spreading ridges the difference is less marked." Smith goes on to remark that the central anomaly (right over the spreading axis) often contains within it a high-amplitude, short-wavelength (~ 15 km) anomaly within it! (R9) This "fine structure" of the magnetic profiles is the subject of X3.

X3. Fine structure of the magnetic profiles. If one would lower a ship-towed magnetometer to just above the ocean floor, one would expect more clear-cut and reliable magnetic profiles across the magnetic stripes on either side of the mid-ocean ridges. The following comments by R.E. Juergens are based upon papers published in the Journal of Geophysical Research and Science.

"The first such deep tow, in 1967, yielded a magnetic profile for a track in the eastern Pacific Ocean in which anomalies, both positive and negative, were ten times more numerous and three to four times more pronounced in intensity than those in a companion profile obtained with a shallow-tow instrument. The investigators contained their astonishment: 'Thus what appears to be a uniformly magnetized crust at the ocean surface is seen to be contaminated with material of differing magnetization at depth.' From the figures and comparisons just cited, this would appear to be something of an understatement.

"The next year, a deep tow farther south in the Pacific Ocean produced a similar profile for another team of researchers. At one particular point along their 'deep magnetics' profile the investigators found that a sharply defined dip corresponded quite nicely to a 'reversal' inferred from surface readings. Their report emphasizes that this dip is characterized with 'about twice the average anomaly amplitude' of the profile as a whole, the plain implication being that here was unequivocal backup evidence for the 'reversal' read into the surface profile. What is not emphasized, however, is that several dips of comparable amplitude, though of lesser width, appear elsewhere along the deep-tow profile, at locations where surface readings give no hint of negative anomalies. The report downgrades these unwanted features as 'the ever present deep magnetic anomalies of lower [sic] amplitude and shorter wavelength' and dismisses them. 'The possibility that each of these anomalies records a short-lived reversal in polarity can be eliminated because no such short-period reversals have been reported from core data [on ocean-bottom sediments].'" (R8)

Given that such fine structure does exist in the near-bottom magnetic profiles, is the sea-floor spreading model capable of explaining it? Juergens, above, pointed out that some of the magnetic fine structure was rejected because it did not correlate with "accepted" geomagnetic history. Below, M.L. Keith suggests that the entire upwelling mechanism is much too coarse to manufacture what is really observed.

"A part of the sea-floor spreading hypothesis is that volcanic eruption or dike intrusion along the ridge axis is the process which is creating both the ridge and the linear pattern of magnetic anomalies. However, it is difficult to reconcile that concept with mounting evidence that the median valley is a sinking system of fault blocks and that young volcanic rocks are deposited on top of older ones over the width of the crest mountains, that is, to 40 or 50 km from the ridge axis. An active volcanic zone of that size is at least an order of magnitude too wide to produce the fine structure of the oceanic magnetic pattern." (R5) The clear implication is that the magnetic stripes are not produced by ambient magnetic field at the time of eruption but rather by some other process. (WRC)

X4. <u>The dating of sea-floor magnetic anomalies</u>. The accurate dating of the magnetic stripes that purportedly parallel the mid-ocean ridges is crucial to the sea-floor-spreading hypothesis. In 1972, A.A. and H.A. Meyerhoff wrote a highly critical analysis of the dating methodology, as it existed at that time.

"The manner in which the anomaly bands are 'dated' must be one of the more flagrant examples of unscientific procedure in history. Although the dates assigned to the anomalies are accepted almost universally, to the best of our knowledge only one possible anomaly source---that of the central or axial anomaly---may have been dated. No others have been identified, sampled, and dated. The number of hypotheses, interpretations, and conclusions that have been published on the basis of totally unproved anomaly dates is staggering." (R7)

Two things bothered the Meyerhoffs, in particular: (1) The assumption that the youngest terrestrial lavas with normal magnetic polarity are equivalent in age to the rocks found at the crests of the mid-ocean ridges; and (2) The assumption that the basalts reached in deepsea drilling away from the ridge axis were truly 'basement' basalts that had been extruded at the mid-ocean ridges, when in fact some cores were either baked, vesicular, interlayered with marble, or of the pillow type. (R7)

The gloomy picture painted by the Meyerhoffs may have improved since 1972, in which case this entry will be revised in future editions. (WRC)

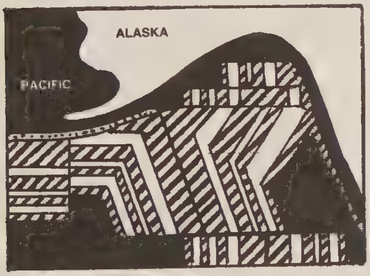
X5. <u>Correlation and continuity of the magnetic stripes</u>. The Meyerhoffs (R7), in addition to questioning the dating of the magnetic bands (X4), also doubted that strong evidence really linked a band in one ocean to one of like age and like polarity in another ocean. Continuity, especially seemed to be lacking (as of the 1972 date of their paper).

"...anomaly continuity breaks down in many places, and particularly in three very large areas with a total length of 12,500 km: (1) a 3,700-km gap from Iceland to the Laptev Sea shelf of northern Siberia; (2) a 1,500-km gap from the south end of the Reykjanes Ridge to the vicinity of the Azores; and (3) a 7,000-km gap from northwest of Bouvet Island south of Africa to the Venus Trench in the northwest Indian Ocean. Other large gaps are present, but these may reflect a lack of control rather than a lack of anomalies. Even so, the fact that 20-25 percent of the world's midocean ridge system is devoid of correlatable anomalies casts doubt on the validity of the correlations made between different ocean basins, and even between different segments of the midocean ridge within the same ocean basin." (R7)

Incidentally, the Meyerhoffs also point

out that the linear magnetic anomalies, or stripes or bands, are approximately concentric around the ancient continental nuclei. They are therefore very, very old and, if so, have no connection with more recent geological history. (R7)

X6. The North Pacific. Looking now at localized anomalous magnetic anomalies, one of the most puzzling is found in the Gulf of Alaska and just below the arc of the Aleutians. Called the Great Magnetic Bight, the bands of magnetic anomalies here take a sudden right angle turn from north to west, as shown in the figure. This sharp corner is itself a confusion of displaced and skewed magnetic bands. In order to explain this remarkable pattern and still retain the sea-floor-spreading hypothesis, geophysicists have supposed that the earth's crust in this region is split into four fragments, which have moved in complicated ways (one displacement up to 280 kilometers) to create the pattern of bands making up the corner or "bight". (R3, R4) This scenario does seem a bit forced. (WRC)



Magnetized stripes of the Great Magnetic Bight south of Alaska. (X6)

Farther south in the Pacific, between the Murray and Molokai fracture zones, one finds a "disturbed" magnetic zone, which has been explained only by assuming the abrupt jump of the midocean spreading center by as much as 530 kilometers. (R6)

X7. The Western Pacific. Another problem area in the Pacific is termed the PJQZ (Pacific Jurassic Quiet Zone). The PJQZ surrounds the Mariana Basin. In this region of the Pacific, proponents of the sea-floor-spreading hypothesis have mapped out strips of normal and reversed magnetic polarity back as far as 153 million years. But before this date, all around the Mariana Basin, ship-towed magnetometers measure very low magnetic anomalies (less than 100 gammas). These low-amplitude magnetic anomalies are taken to be natural extensions of the mapped areas and, therefore, older than 153 million years.

To explain the great reduction in amplitude, geophysicists have supposed: (1) The low-amplitude magnetic anomalies were created during periodic reductions in the strength of the earth's dipole magnetic field, but without actual reversals; and (2) The earth's dipole field did reverse itself but its strength was greatly reduced when the PJQZ was being extruded. (R10)

In the above context, it should be noted here that terrestrial magnetic anomalies are usually assumed to be due to reductions in dipole strength rather than reversals. (R8)

X8. The Atlantic Ocean. In the Atlantic, we find no 90° bights, but skewness has been noted, as in this Abstract by S.C. Canda.

"Marine magnetic anomalies 33 and 34, corresponding to the first two reversals following the long normal polarity interval in the Cretaceous, are anomalously skewed by 30° to 40° throughout the North and South Atlantic. This phenomenon is most likely related to some aspect of the dipole paleomagnetic field. Specifically the magnetic field at the time of anomalies 33 and 34 appears to be characterized by the following: the dipole field gradually decreases in average intensity between reversals and/or there is an increase in the frequency or duration of undetected short polarity events toward the end of long periods ($\sim 10^6$ years) of predominantly one polarity. Such long-period trends in the field are in conflict with the popular model for the generation of the earth's magnetic field that treats reversals as a Poisson process and assumes that the core has no memory greater than about 10^4 years." (R9)

An enigma of a different sort was encountered during deep drilling into the seafloor by the Glomar Challenger in the 1970s. J.M. Hall and P.T. Robinson alluded to this in their 1979 paper in Science describing operations in the North Atlantic.

"Drilling has shown convincingly that the source of the [magnetic] anomalies does not lie in the upper 600 m of oceanic crust as previously thought. Are the anomalies generated by considerable thicknesses of low-intensity material or is there some highly magnetic source layer at greater depth? If so, what constitutes the layer and why is it not tectonically (and thus magnetically) disrupted in the same way as upper layer 2? These questions can only be answered by deeper crustal drilling." (R14)

Questions about the location and origin of these magnetic anomalies strike at the heart of magnetostratigraphy and plate tectonics. (WRC)

X9. Sea-floor spreading and the expanding-earth hypothesis. The accepted interpretation of plate tectonics allows no rapid expansion of the earth, as championed by S.C. Carey. (See ETL.) However, detailed mapping of magnetic striping seems to require, in the eyes of some, a modest amount of expansion. This was explained by W.B. Harland as follows.

Using magnetic striping, "the course of ocean spreading has been delineated with considerable precision so that latterly the problem was to estimate how far this generation of new crust was compensated by the much-more-difficult-to-estimate subduction in orogenic belts. H.G. Owen (British Museum (Natural History)) has plotted the striping in a series of detailed maps that also require a more modest, but nevertheless significant, expansion of the Earth during the past 200 Ma at least. Owen's expansion is less than Carey's because he recognizes the evidence of subduction zones. It might be added that most plate tectonic reconstructions seem to get by with a steady size Earth but they generally do not plot ocean floor spreading details. In this respect Owen's work is so thorough that it cannot be ignored." (R12)

References

R1. Strahler, Arthur N.; "Objections to Seafloor Spreading," Science and Earth History, Buffalo, 1987, p. 204. (X0)
R2. Ewing, Ann; "Shift in Crust Found," Science News, 89:347, 1966. (X6)
R3. "How the Great Magnetic Bight Came into Being," New Scientist, 40:681, 1968. (X6)
R4. Beloussov, V.V.; "Against the Hypothesis of Ocean-Floor Spreading," Tectonophysics, 9:489, 1970. (X6)
R5. Keith, M.L.; "Ocean-Floor Convergence: A Contrary View of Global Tectonics," Journal of Geology, 80: 249, 1971. (X1, X3)
R6. Harrison, C.G.A., and Sclater, J.G.; "Origin of the Disturbed Magnetic Zone between the Murray and Molokai Fracture Zones," Earth and Planetary Science Letters, 14:419, 1972. (X6)
R7. Meyerhoff, A.A., and Meyerhoff, Howard A.; "'The New Global Tectonics': Age of Linear Magnetic Anomalies of Ocean Basins," American Association of Petroleum Geologists, Bulletin, 56:337, 1972. (X1, X4-X6)
R8. Juergens, Ralph E.; "Geogullibility and Geomegnatic Reversals," Kronos, 3:52, Summer 1978. (X3, X7)
R9. Smith, Peter J.; "Central Anomalies: Why So Strong?" Nature, 260:486, 1976. (X2)
R10. Smith, Peter J.; "Pacific Quiet Zone Contracted," Nature, 277:604, 1979. (X7)
R11. Canda, Steven C.; "Anomalous Behavior of the Paleomagnetic Field Inferred from the Skewness of Anomalies 33 and 34," Earth and Planetary Science Letters, 40:275, 1978. (X8)
R12. Harland, W.B.; "An Expanding Earth?" Nature, 278:12, 1979. (X9)
R13. Beloussov, V.V.; "Why I Do Not Accept Plate Tectonics," Eos, 60:207, 1979. (X1)
R14. Hall, J.M., and Robinson, P.T.; "Deep Crustal Drilling in the North Atlantic," Science, 204:573, 1979. (X8)

EZC4 Selected Geographically-Specific Anomalies of the Geomagnetic Field

Description. Strong deviations of the strength and/or direction of the geomagnetic field from the parameters expected for an ideal dipole field.

Data Evaluation. A large literature is available from scientific research programs and geophysical prospecting for minerals. From this body of references, we select here only a few especially interesting magnetic anomalies. Many more doubtless exist. Rating: 1.

Anomaly Evaluation. The unusual features of the geomagnetic field recorded below may be explained in several ways: (1) By large, buried ore bodies (possibly even meteoritic masses); (2) Subcrustal structures, such as folds or chunks of subducted crust; and (3) Departures from the flow patterns of the core material now believed responsible for the generation of the geomagnetic field. Because no one has been able to directly sample the crust, mantle, or core at the required depths, all interpretations of these geomagnetic anomalies are tentative. In such a situation, the phenomenon must be regarded as only mildly anomalous. Rating: 3.

Possible Explanations. See above.

Similar and Related Phenomena. The other magnetic anomalies recorded in this chapter (EZC); anomalies of the general geomagnetic field (EZF).

Examples

X1. The Great Arctic Magnetic Anomaly. One remarkable geomagnetic anomaly is found in the arctic regions of the northern hemisphere, as sketched by L.R. Alldredge and G. Van Voorhis.

"The magnetic field of the earth exhibits two maxima of vertical intensity (Z) and very elongated horizontal intensity (H) contours in the arctic regions. One of the dipoles is located in Siberia and the other in northern Canada. These two Z poles are accompanied by very similar total intensity (F) maxima. Magnetic meridians draw very close to each other near the geographic pole and then proceed as a bundle of nearly straight lines towards the north magnetic pole. This unique pattern of magnetic elements has been described by Hope as the great arctic magnetic anomaly.

"Hope has ascribed this anomaly to geologic sources lying deep within the earth's crust but above the Curie-point level. He suggests that the magnetic anomaly is associated with a Mesozoic folding which crosses the Arctic Ocean from the New Siberian Islands to Ellesmere Island.

"This paper demonstrates that all of the known unique features of the great arctic anomaly can be accounted for by magnetic sources at the core-mantle interface. Such an explanation is not handicapped by serious questions caused by unusual crustal structure and thermal conditions, which are a part of geologic explanations." (R1)

A quite different interpretation of what seems to be the same anomaly has been offered by J. De Laurier, a Canadian scientist. What follows is from a newspaper account of De Laurier's work.

"...there's something mysterious down there---as much as 18 miles down---that causes a magnetometer to register a higher magnetic reading than it should. And it stretches about 43 miles wide along a 450-mile path between the isolated northern settlement of Alert and Eureka."

.....

"The anomaly was discovered first at Alert in 1957, and each successive year its spreading size has been charted.

"'There are other such anomaly features around the world---such as down in the Rocky Mountains in the United

States, in fact wherever there are recognized earthquake zones,' [De Laurier] said.

"'But ours is enormous and could be larger than any of them. In fact, there's another anomaly connected with the Canadian one. It's not on an earthquake zone---the Arctic doesn't have earthquakes, it's very stable.'

"He said one theory suggests that such a build-up in magnetic forces comes where the plates, upon which the continents are built, rub together, a cause of earthquakes.

"'But that doesn't explain our anomaly, and so far we can't find an explanation for it. It's a total mystery.'" (R2)

X2. Bangui: An African magnetic anomaly.

"The Bangui anomaly, centered at 6°N, 20°E, is one of the largest and most impressive magnetic anomalies on Earth. It is certainly the largest anomaly over Africa. At Magsat altitudes (375 km), it has an amplitude of -28nT relative to flanking positive anomalies to the north and south. The area of intense negative anomaly is about 700,000 sq. km. A negative Bouguer anomaly reaching -100 mGal covers approximately the same area.

"At the surface, the anomalies are associated with the Oubangui Basin containing Palaeozoic sedimentary rocks. These can explain the Bouguer anomaly, but not, of course, the large, intense negative magnetic anomaly. The magnetic anomaly must be due to a subsurface, deeper body. There seem to be two possibilities: (1) a very large basic igneous intrusion underlying the sedimentary basin or (2) a much smaller strongly magnetized body at depth. We examine the advantages and disadvantages of both.

"The first requires unreasonably high magnetization contrasts even for very basic igneous rocks, implying a high density and making it difficult but not impossible to explain the negative gravity anomaly. For the second, we assume the presence of an iron-rich body and estimate its size for various magnetization contrasts. Various possible explanations for the nature of the iron-rich body are explored." (R4) As pointed out in EZC3, terrestrial magnetic anomalies are not usually explained in terms of reversed magnetization of rocks, as in the case of ocean-floor anomalies. (WRC)

X3. Stationary lobe-like features of the geomagnetic field. Using historical records of the surface geomagnetic field from 1715 through 1980, J. Bloxham has, with the help of "new mathematical methods", mapped the geomagnetic field at the surface of the earth's core over the past 265 years. As generally expected, the field in the polar regions of the core remained essentially fixed, but so also did four lobes of high magnetic flux located symmetrically on either side of the equator at 60° latitude and at longitudes of 120°E and 120°W.

"That the four lobes have stayed in place for nearly 300 years is surprising, says Bloxham. Traditionally, scientists have envisioned the entire field as drifting westward across the face of the planet at about 0.2° per years because the core rotates more slowly than do the mantle and crust. If the four lobes had been drifting at 0.2° per year, they would have moved by over 50° longitude since 1715.

"'We can be quite certain that westward drift is not happening everywhere at the core surface,' says Bloxham. 'Since the lobes are staying put, this indicates that something is keeping them there.'" (R3)

Bloxham and D. Gubbins venture that these four lobes, while probably consistent with dynamo models of the geomagnetic field, are anchored in place by the mantle, which convects much more slowly than the core. A rather startling observation has been made by P. Olson, who likens the four lobes to pairs of sun spots, which are also located symmetrically about the sun's equator and are, in addition, magnetic in nature. (R3)

X4. The Paris Basin magnetic anomaly. A strong magnetic anomaly spans the entire Paris Basin in a north-south direction. Geophysicists had surmised that this anomaly arises from a long band of magnetic rock buried under 3 kilometers of overburden. When the Sancerre-Couy borehole, 150 kilometers south of Paris, reached that depth, it was expected that bits of this magnetized rock would be retrieved. But the hole bottomed at 3.5 kilometers without any sign of the hypothesized magnetized body of rock. (R5)

References

R1. Alldredge, Leroy R., and Van Voorhis, Gerald; "Source of the Great Arctic Magnetic Anomaly," Journal of Geophysical Research, 67:1573, 1982. (X1)

R2. Quinter, David; "Scientist Pursues 'Mystery' in Arctic," Toronto Star, March 20, 1974. (X1)

R3. Weisburd, Stefi; "The Inner Earth Is Coming Out," Science News, 131: 222, 1987. (X3)

R4. Girdler, R.W., et al; "Some New Thoughts on Bangui," Eos, 70:314, 1989. (X2)

R5. Kerr, Richard A.; "Deep Holes Yielding Geoscience Surprises," Science, 245:468, 1989. (X4)

EZC5 Earth-Current and Electrical-Conductivity Anomalies

Description. (1) Direct measurements of anomalous earth currents by means of buried electrodes; viz., in X1, the 16 symmetrical eddies of earth currents that follow the sun. (2) Anomalous behavior of natural variations of the geomagnetic field, implying unrecognized buried geological structures.

Data Evaluation. The scientific literature devoted to earth currents and conductivity anomalies is large and impressive. Our small bibliography here results from our survey of general-science and geology journals. The specialized journals contain much more. Rating: 1.

Anomaly Evaluation. (1) The pattern of 16 magnetically-induced, sun-following, earth-current eddies (X1) probably has an explanation involving the solar wind impinging upon the earth, but the reason for the specific number and arrangement of the eddies is elusive. (2) Deeply buried conductivity anomalies are often correlated with seismicity and heat-flow anomalies. In some cases, partial melting of the crust and mantle may be implied; in other cases, conducting aqueous fluids may exist at great depths. This latter situation is contrary to the prevailing assertion that aqueous fluids are restricted to the uppermost levels of the crust. Generally speaking, these anomalies will require only modest changes in scientific thinking. Rating: 3.

Possible Explanations. See above.

Similar and Related Phenomena. Thermal plumes (ECH); anomalous structures in the crust and mantle, as revealed by seismology (EQA, EQD).

Examples

X0. Introduction. The earth's crust, mantle, and core are electrically conducting. To illustrate, the geomagnetic field is thought to be created by self-excited dynamo action, which depends upon the motion of electrically conducting material in the core. However, electical currents also flow at all depths, in vertical and horizontal directions. Only at the surface can we measure these currents directly with buried electrodes. Deeper currents and the conductivity of the rocks they flow in are inferred from variations of the geomagnetic field. It is now apparent why earth currents and conductivity are included in the chapter.

The sole entry below relying upon the direct measurement of earth currents is X1, in which the well-established pattern of 16 "eddies" of superficial currents is reported. All other entries are the consequence of analysis of the geomagnetic field. These latter anomalies are usually termed "conductivity anomalies", although sometimes the phenomena are described in terms of subterranean currents. To introduce the subject of conductivity anomalies, we quote the Abstract of a paper by Y. Honkura that appeared in Geophysical Surveys in 1978.

"Anomalies of short-period geomagnetic variations have been found in various regions over the world. It is known that such anomalies arise from electromagnetic induction within an electrical conductivity anomaly or from local perturbation of induced electric currents by a conductivity anomaly. In order to investigate a regional electric state in the Earth, conductivity anomaly (CA) studies based on anomalous behaviors of geomagnetic variations have been extensively undertaken, as well as studies based on magnetotellurics in which induced currents are directly used."

.....

"Electrical conductivity anomalies can be classified into two types: anomalies originating in the crust and in the upper mantle. Many crustal anomalies are well correlated with metamorphic belts, fracture zones, and hydrated layers; and magnetic and gravity anomalies are also found over the conductivity anomalies. Most of the mantle anomalies have been interpreted mainly in terms of high temperature and partial melting, since conductivity anomalies coincide well with anomalies in heat flow and seismic wave velocities." (R5)

In the body of his paper, Honkura reviews the evidence linking conductivity anomalies with tectonic plate boundaries in Japan, the Peruvian Andes, Iceland, the East African Rift Valley, etc. It is obvious that electrical-conductivity anomalies can be very important in exploring the constitution of "inner earth".

X1. Superficial eddies of earth currents. This phenomenon was discovered through the study of direct earth-current measurements at many stations around the globe.

"Discovery of electrical circuits in the earth's crust that whirl around a number of points, both in the polar regions and in more temperate climes, was reported to the International Union of Geodesy and Geophysics in Edinburgh by O.H. Gish and W.J. Rooney of the Carnegie Institution of Washington's Department of Terrestrial Magnetism.

"The crustal electric currents are believed to form 16 extensive eddies. Eight of these are located in the middle and low latitudes. Four in the Northern Hemisphere and four in the Southern Hemisphere form a symmetrical arrangement about the equator. The centers of these eddies are about equally spaced in longitude and lie near the tropics of Cancer and Capricorn, respectively.

"Four other eddies also appear in high northerly latitudes with their centers near the arctic circle. These also are about equally spaced in longitude. A corresponding set of eddies presumably exists in high southerly latitudes, but data to establish the fact are not available." (R1)

The 16 eddies follow the sun so that 8 of them are always on the sunlit side of the earth with the other 8 on the dark side. O.H. Gish, the researcher mentioned above, asked five questions about these eddies in an encyclopedia article: "(1) Why should the worldwide system of electric eddies be fixed with respect to the Sun? (2) Why should it be most intense on the daytime side of the Earth? (3) Why should it shift with season? (4) Why should it vary with sunspot number? (5) Why is there a lunar diurnal variation?" (R10) Gish does not answer his questions in the article, but the sun plays an obvious role. However, it seems likely that these eddy currents are induced by the geomagnetic field, which is itself modulated by the solar wind. This could be the mechanism that creates the eddies, but why are there 16 well-defined eddies, none of which are centered on the earth-sun line?(WRC)

X2. The "hot spot" under the Andes. "A 'hot spot,' discovered deep within the Andes Mountains of Peru and Bolivia, is being studied by an international team of scientists.

"The 'hot spot' is an area of high electrical currents 12 to 24 miles beneath the Andes. It is believed to be related to huge crustal movements associated with earthquakes and active volcanoes in that region.

"It was discovered last October during research by Carnegie Institution and the Instituto Geofisico del Peru."

The scientists remarked that the currents were so large that they overwhelmed the "ocean edge effect" caused by electrical currents in the salty ocean waters nearby. (R2) Note that ocean currents carry electricity and thus contribute to perturbations in the the earth's magnetic field. (WRC)

X3. Northern France and the Channel Coasts. J.C. Rossignol introduced his 1972 report in *Nature* be remarking that differences in variations of the earth's magnetic field between 10 and 120 minutes long had been observed at sites along the west of Britain. Geophysicists have interpreted these differences as being due to a channel of high electrical conductivity under Ushant Island. In his own field research, Rossignol found other such anomalies in northern France and along the Channel. That these channels of high conductivity are rather mystifying comes out clearly in Rossignol's concluding paragraph.

"This study has shown the existence of anomalies of electrical conductivity along the channel coasts and in northern France. The measurements contributed to the recognition of such anomalies in western Europe. It seems as if the anomalies of the region can be classified into those for which the influence of superficial strata is predominant and others for which the influence of deeper regions of the Earth is most important. Magnetorelluric observations should help to remove the outstanding uncertainties." (R3)

X4. Australia. Variations in the vertical component of geomagnetic fluctuations have been reported from seismically active areas of Australia. Using these data, geophysicists have plotted two channels of high electrical conductivity: (1) the Flinders Conductor along the eastern edges of the Flinders Ranges; and (2) the Otway Conductor in southern Victoria. (R4) Geophysicists are not certain why seismicity and high electrical conductivity should be related. (WRC)

Another channel of high conductivity has been discovered by other Australian geophysicists under Broken Hill, New South Wales. This channel may simply be an extension of the Flinders Conductor, for the two are geographically close. The article reporting this discovery begins as follows.

"Geophysicists from the Department of Earth Sciences and the Bureau of Mineral Resources have discovered part of a huge underground circuit near Broken Hill, which contains electric currents of more than a million amps.

"The currents are spread too thinly for power production, but their existence helps account for problems experienced generally in interpreting the magnetic data used to produce geological maps." (R9)

The Strait of Georgia between Vancouver Island and the mainland is the site of a strong current of terrestrial electricity. Arrows mark its flow. (X5)

X5. The Pacific Northwest. "An immense current of terrestrial electricity originating somewhere in the Pacific enters the North American continent along the Strait of Georgia (between Vancouver Island and the mainland of British Columbia) and shoots past Tacoma down toward Oregon. The discoverers of the current, J.R. Booker and G. Hensel, at the University of Washington, traced the flow of electricity through a narrow wedge of porous, water-bearing rock that parallels a fault line. Another branch of this terrestrial circuit enters along the Strait of Juan de Fuca. No estimates are given of the magnitude of the current; and there are no speculations as to the origin of the electromagnetic force driving the current. (R6)

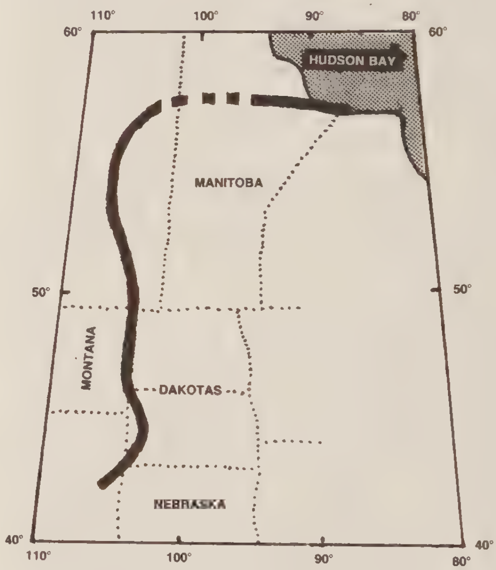
X6. Arizona. The research of J.N. Towle in Arizona exemplifies modern research on deeply buried channels of high conductivity---it has become a highly technical enterprise. We quote here from the Conclusion of his 1984 paper.

"The anomalous GMV [geomagnetic variation] field in the vicinity of the San Francisco Peaks volcanic field is caused by a regional telluric current system flowing parallel to the Mesa Butte and Bright Angel fault systems as described by Shoemaker and others. The axis of a concentration of telluric currents within this system coincides with the eastern margin of the Mesa Butte fault system. The shallow portions of this local telluric current concentration are at a depth of not more than 10 km. A lack of obviously conductive geologic structures at the surface suggests that the telluric current concentration is caused by fundamental geoelectric structures in the crust associated with the Mesa Butte fault system.

"Further support for a conductive structure in this region comes from recent magnetotelluric measurements. M.E. Anders noted a qualitative changes in a profile of magnetotelluric measurements across northern Arizona. Magnetotelluric soundings southeast of Flagstaff and near Park, Arizona, indicated shoaling to perhaps 10 to 20 km of a 5-50 ohm-meter conductor that lies at 40 km near Winona and to the east.

"The regional telluric current system is polarized N55°E and suggests a conductive fabric throughout the region parallel to the Mesa Butte, Bright Angel, and Sinyala fault systems. This conclusion is significant in that telluric current flow is likely to be associated with deep and extensive crustal and upper-mantle features." (R7)

X7. The North America Central Plains (NACP) conductivity anomaly. The NACP conductivity anomaly snakes west from Hudson Bay, then south into the States, and wiggles a bit before terminating in Wyoming. As delineated by magnetic surveys, it is over 2,000 kilometers long, and may be longer and wider than shown on the map. Since the top of this belt of high electrical conductivity rock is some 10 kilometers below the surface, no one is sure of its constitution---graphite in schistose rocks is one guess. Its meaning for the geology of North America is also a mystery---it could be the edge of a buried tectonic plate. Whatever it is, it is important. It is "the largest and most enigmatic continental-scale structure discovered to date by electromagnetic induction studies." (R8)



The dark streak looping west and south from Hudson Bay represents the North America Central Plains (NACP) electrical conductivity anomaly. It was mapped through magnetometer surveys. (X7)

X8. A general observation. The forgoing examples of high-conductivity channels deep in the earth's crust are merely representative; there are many others worldwide. The frequent occurence of high-conductivity regions at depths of 15-20 kilometers and more have led to the suggestion that aqueous electrically conducting fluids persist deep down into the crust. Such a situation would be anomalous because conventional wisdom (as of 1986) states that the lower crust (below 15-20 kilometers) must be dry. In this connection. it should be noted that the Soviet's deep borehole on the Kola peninsula found fluids at 12 kilometers. (R10)

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EZF CONFIGURATION ANOMALIES AND SECULAR VARIATIONS OF THE GEOMAGNETIC FIELD

Key to Phenomena

EZF0 Introduction

It is accepted that the geomagnetic field resembles that of a dipole (or bar magnet) located at the earth's center. This theoretical representation accounts for about 90% of the geomagnetic field and provides geophysicists with the familiar diagram showing magnetic lines of force exiting one polar region and entering the other. This neat portrait of the geomagnetic field is marred in practice by several important anomalies that cast doubt upon the almost universally accepted view that the geomagnetic field is a product of dynamo action.

First, the axis of the steady-state geomagnetic field does not lie parallel to the axis of rotation. Second, there exists a significant (10%) non-dipole field. Third, the non-dipole field is of complex structure and undergoes unpredictable secular changes, such as drifting, sudden acceleration, and shifts in configuration.

Despite these anomalies, the geodynamo theory is the only one that even comes close to explaining the observed configuration and variability of the geomagnetic field. The geomagnetic field's axial tilt and secular variation are both difficult-to-account-for using the dynamo model, as are other geomagnetic observations. But, as if to compensate, the geodynamo's shell of electrically conducting fluid, which is stirred by heat, forces of rotation, earthquakes, etc., offers many opportunities to explain complex phenomena. In other words, the potential complexity of the geodynamo matches the observed complexity of geomagnetic phenomena. Nevertheless, it does seem risky to rely so completely and uncritically upon a single theoretical concept.

EZF1 Anomalies of the Steady-State Geomagnetic Field

Description. Departures of the geomagnetic field from that of an ideal dipole positioned at the earth's center and parallel to the planet's axis of rotation.

Data Evaluation. General descriptions of the earth's magnetic field abound in both scientific and popular literature. It is interesting to note, however, that the geographical positions given for the magnetic poles (the so-called "dip poles") cover a wide range. Rating: 1.

Anomaly Evaluation. As detailed in X0, below, the dynamo theory of the origin of the geomagnetic field is almost universally accepted. The inclination of the geomagnetic field's axis to the axis of rotation is incompatible with this theory. To retain the dynamo theory, small, additional dipoles and/or other changes in core configuration must be assumed. Further, the presence of large-scale geomagnetic anomalies requires similar "tuning" of the dynamo model. At present, no one seems to know just how "supplementary" dipoles and other such modifications would work physically. These anomalies seem all the more serious because geophysicists insist that the dynamo theory is the only viable one. Rating: 1.

Possible Explanations. Complex circulation patterns, perhaps even turbulence, may combine to cause the observed departures from the ideal dipole field, but these "band-aids" simply underscore our ignorance about chemical and physical processes transpiring beneath the crust. Other generators of magnetic fields may exist, such as thermoelectrically-driven electric currents and conducting fluids circulating well outside the core proper.

Similar and Related Phenomena. Secular changes (EZF2); extraterrestrially induced transients of the geomagnetic field. (The latter are not considered anomalous here.)

Examples

X0. Introduction and baseline theory. The fact of the earth's magnetic field has been apparent for centuries, but its elucidation has been much more difficult than its detection. The geomagnetic field is rather weak when compared to magnets of human manufacture, but it is strong compared to the fields of the other terrestrial planets. At the equator, the total magnetic intensity is about 0.3 gauss. This increases to about 0.7 gauss in the polar regions. The geomagnetic field can be approximated by a dipole, located at the earth's center, tilted about 11° to the axis of rotation. This tilting of the magnetic axis remains an anomaly---one that also prevails on some other solar-system planets. The "tilt" problem will be treated in X1 and X2. Another sort of anomaly becomes apparent when one subtracts the magnetic intensity calculated for the ideal dipole from the measured geomagnetic field. These deviations (the "non-dipole" field) exhibit structures hundreds, even thousands of miles in extent. Such structures are termed "magnetic anomalies"; and here the use of the word "anomaly" is consistent with usage in the Catalog of Anomalies. These large-scale magnetic anomalies are covered in X3. See ESC for small-scale magnetic anomalies.

One of the greatest problems in geophysics is the development of a mechanism that will generate the observed geomagnetic field with all its steady-state anomalies (ESF1) and the so-called secular changes (ESF2). This problem is deemed so important that an entire section (ESF3) is devoted to it.

Three important facts severely constrain speculation about field-generating mechanisms; and they should be brought forward at the outset: (1) The temperature of the earth rises rapidly as one drills down through the crust. By extrapolating these measurements, it can be asserted that at depths of just 100 kilometers or so, temperatures have surpassed the Curie point of known materials, and it is too hot for magnetism to exist. (2) Secular changes of the geomagnetic field occur too rapidly to be accounted for by solid, permanently magnetized materials. (3) The electrical resistance of core materials---as predicted from present models of the earth's interior---is too high for the earth's field to be generated by deep, still-circulating, primordial electrical currents, assuming that the earth is billions of years old. These restrictions do not preclude the generation of the geomagnetic field through dynamo action, thermoelectrically generated currents, or other on-going physical processes. See ESF3.

In most modern scientific books and papers, it is stated dogmatically that the dynamo theory is the only viable theory. This is an extreme statement in the light of the difficulties the geodynamo theory encounters. It is safer to hedge a bit, as in the following quotation from H. Takeuchi et al:

> "What is the origin of the geomagnetic field? Many a hypothesis has been offered and rejected. The fairest answer at present would be that the geomagnetic field is caused by electric currents within the core, and that these currents are probably induced and maintained by a mechanism such as the self-exciting dynamo. The dynamo theory is certainly by far the best yet offered. It is not perfect, but it surpasses all others by a wide margin." (R3)

As users of the Catalog of Anomalies might surmise, the compiler ventures that we do not yet know enough about deep-earth processes to restrict ourselves dogmatically to the geodynamo model.

X1. The tilt or inclination of the axis of the geomagnetic field to the earth's axis of rotation. It is not difficult to determine the earth's axis of rotation from astronomical measurements; the precise position of the geomagnetic axis is more difficult to locate. In principle, one can locate the geomagnetic poles either by finding the two spots, north and south, where the compass needle (actually an inclinometer here) points straight down or by pinpointing the spots where northerly and southerly compass readings converge. In practice, however, neither procedure is very accurate due to the erratic behavior of compasses in the polar regions. Wildly different pole positions may be found in the literature, as recorded in X2. Alternatively, one can combine aircraft and satellite magnetic measurements and determine the inclination of the dipole that best fits them. In this way, geophysicists have decided that 90% of the geomagnetic field is dipolar in nature, and that the dipole representing this part of the field is inclined 11° to the axis of rotation. (R13; R3, R11, R12, R14)

The tilt of the earth's magnetic field and those of the other planets (especially Uranus, 60°; and Neptune, 47°) seriously challenge the dynamo theory of field generation, since this theory relies on the planet's rotation. (See ESF3.) The way in which geophysicists deal with the tilt anomaly, as well as other anomalies of the geomagnetic field, is to suppose there are secondary dipole fields created at "spots" near the surface of the liquid core. S. Akasofu and T. Saito, for example, think that two or three such extra dipoles effectively tilt the magnetic fields of all the planets afflicted by this divergence of axes. In their theory, the axis of the main dipole field remains parallel to the axis of rotation, but the secondary dipoles warp the total field. (R11, R12, R14) K. Whaler has objected that there exists no known physical mechanism for creating such secondary dipoles near the liquid core's surface. (R12)

It may be possible to conceive of complex circulation patterns in the earth's liquid core that can account for just about any distortion of the basic dipole field. But then one must explain the complex circulation patterns! It might be better, but not necessarily easier, to search for other ways in which the geomagnetic field might be generated. (WRC)

X2. Is the geomagnetic axis offset? In the preceding discussion of the tilted geomagnetic axis, it was tacitly assumed that this axis went through the center of the earth, where it intersected the axis of rotation. If the geomagnetic axis were offset as well as nonparallel to the axis of rotation, the dynamo theory would be in additional difficulty.

The only evidence that an offset axis might be a reality arises from the great discrepancies in the published positions of the geomagnetic poles, as in the accompanying table. As mentioned earlier, accurate location of the poles with compasses is a daunting task. Even so, the range of quoted values is very large. The entries from R3, in fact, were apparently computed from the accepted 11° tilt of the ideal dipole, for the poles are precisely 180° apart. In other words, they were not located from the ground by compasses but rather from the position of the ideal dipole. But the other values allow the possibility of an offset or possibly a "crooked" geomagnetic axis.

Geographical positions of the poles

North magnetic pole		South magnetic pole		
Lat.	Long.	Lat.	Long.	Ref.
---	96°W	---	155°E	R1
78.5°N	69°W	78.5°S	111°E	R3
77°N	102°W	65°S	139°E	R9
77.3°N	101.8°W	---	---	R16
76.1°W	100°W	65.8°S	139°E	R17

In 1930, O.J. Lee published a letter in Science pointing out the possibility of offset poles and appending a catastrophic interpretation.

"A remarkable asymmetry exists in the longitude of the earth's magnetic poles, which are at present [1930] in 96° west and 155° east longitudes. They are, therefore, only 109° apart, and their longitudes mark out roughly the average boundaries of the Pacific Ocean, the vast basin of which has many 'deeps' and is enclosed by a giant circlet of extinct and active volcanoes. If this basin is the birthplace of the moon, it does not seem unreasonable to expect that enough of the heavier, deep-lying magnetic elements in the earth may have been torn along, placenta-wise, on that natal occasion to actually fix the magnetic poles of the earth in these regions. Perhaps it would be better to say that when the lunar material departed, a shift in the distribution of magnetic materials within the remaining mass took place toward the Pacific basin." (R1)

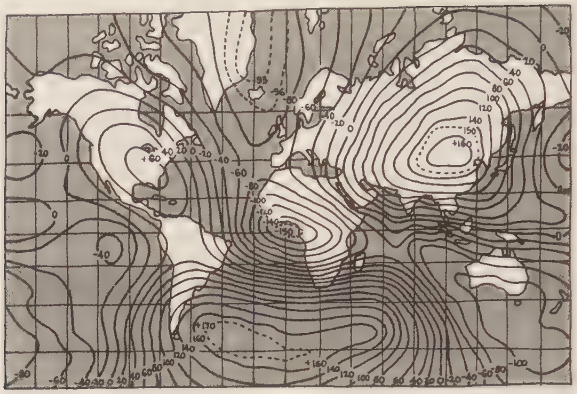
This non-antipodal arrangement of the earth's magnetic poles was widely accepted in the 1930s and was even associated with the onset of continental drift. (R2) Today, however, the possibility of an offset or crooked geomagnetic axis is rarely considered. Any evidence for such situations is explained away as distortion of the dipole field due to secondary dipoles on the core surface. (WRC)

X3. Large-scale, non-dipole aspects of the geomagnetic field. The non-dipole geomagnetic field (sometimes called the "geomagnetic anomaly") is what remains after the dipole field has been subtracted out. Some large-scale departures from the dipole field are obvious. (R3)

Thousands of miles in extent, these magnetic anomalies dwarf the much smaller anomalies tendered in EZC. About all that can be said about these large-scale anomalies in the way of explanation is that they are "probably" due to structures deep within the earth, whereas the small-scale EZC anomalies are superficial. It is possible, however, that these "structures" may derive from the geodynamo itself.

A new perspective on large-scale magnetic anomalies has been drawn by J. Bloxham and D. Gubbins. Their technique involves mathematically projecting surface measurements of the geomagnetic field down to the surface of the earth's liquid core, where the field is thought to originate. To do this Bloxham and Gubbins must make assumptions about the physical properties of the crust and mantle, such as their electrical conductivities. By using past measurements of the geomagnetic field, they can chart recent changes on a global basis.

The field at the core's surface shows areas of strong departure from the dipole field. For example, an especially strong concentration of flux exists at the core surface positioned below the South Atlantic Ocean. More startling is the suggestion by Bloxham and Gubbins that the surface dipole field actually derives from four "patches" on the core surface. The magnetic fluxes from these patches combine at the surface to give the "illusion" of a mainly dipole field! (R8, R15) If the calculations of Bloxham and Gubbins are correct, and these patches are real, the geodynamo must be configured accordingly. (WRC)



Anomaly of the vertical component of the intensity of the geomagnetic field. The unit is 1 x 10^{-3} gauss. (X3)

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R15. Bloxham, Jeremy, and Gubbins, David; "The Evolution of the Earth's Magnetic Field," Scientific American, 261:68, December 1989. (X3)
R16. Dalrymple, G. Brent; "Can the Earth Be Dated from Decay of Its Magnetic Field?" Journal of Geological Education, 31:124, 1983. (X1, X2)
R17. Cain, Joseph C.; "Geomagnetism," McGraw-Hill Encyclopedia of Science and Technology, 6:154, 1977. (X0-X2)

EZF2 Secular Variations of the Geomagnetic Field

Description. Changes in the parameters describing the geomagnetic field on a time scale of a year or more. The parameters usually involved are those of the non-dipole field and may include the formation, change-in-shape, and geographical movement of patches of flux and other structures of the non-dipole field.

Data Evaluation. Over a century's worth of high-quality geomagnetic measurements are available. Rating: 1.

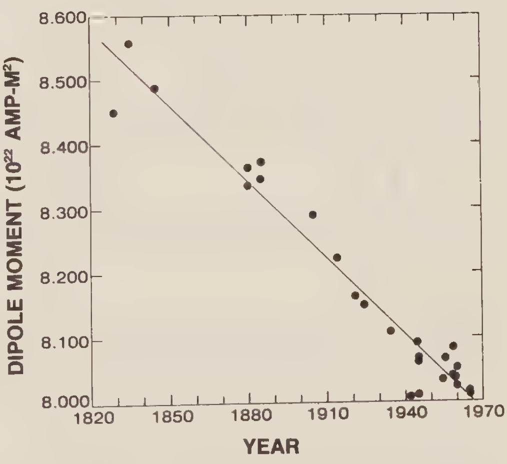
Anomaly Evaluation. The overall impact of the whole panoply of secular variations of the geomagnetic field is that the phenomena are extremely complex in terms of time, geography, and radial location (earth's surface or core-mantle boundary). The anomalousness of each aspect of secular variation depends upon how well the reigning dynamo theory can accommodate the complexities. Seeing that the electrically conducting fluid of the geodynamo can exhibit eddies, internal waves, convection cells, turbulence, and even chaotic motion, we have at hand a field-generating mechanism that may be up to almost any assigned task! Therefore, we cannot assign a high anomaly rating here. Rating: 3.

Possible Explanations. As above. See also ESF3 for other theories of the geomagnetic field.

Similar and Related Phenomena. The decay of the geomagnetic field (EZF1); pole wandering (EZP3); paleomagnetism correlated with climate changes (EZP5).

Examples

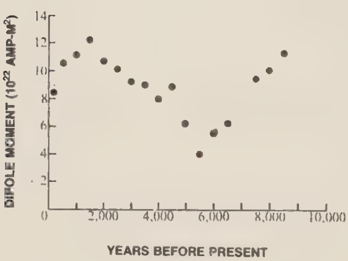
X0. Introduction. "Secular variations" of the geomagnetic field occur on a scale of roughly a year or more, shorter-scale variations being termed "transients". In geophysical parlance, "secular variation" is primarily applied to the slow westward drift of certain features of the geomagnetic field, such as the lines of equal declination. However, there are other secular variations, like the historical decay of the magnetic moment of the geomagnetic field. This broader interpretation of the word "secular" is employed here.



X1. The historical decay of the geomagnetic field. Measurements of the magnetic moment of the dipole component of the geomagnetic field since 1835 show a steady decrease of about 0.05% per year. (R26) This amounts to 5% per century and is a large change for a geophysical variable storing so much potential energy. The implication is that if this rate of decay persists, the earth's magnetic field will vanish in only 2000 years or so. This undeniable trend raises important scientific and practical questions.

Will this decay of the field continue? Of course, no one can predict the future with certainty: the trend may reverse; the geomagnetic field may become null and then reverse polarity; or the field may even disappear permanently. In this situation, an appeal to archeomagnetic measurements involving dated pottery assures us that the geomagnetic field has had its ups and downs over the last several thousand years. In other words, secular decreases have happened before. (R7, R23) In fact, the present geomagnetic field is much stronger than it has been, on the average, over the long term. (R26) Looking backwards in time ever farther, paleomagnetic research tells us that a geomagnetic field existed as far back as 2.7 billion years ago. (R14) In addition, outright reversals of the field seem to have occurred frequently over geological time. (See EZP.) All things taken, it is likely that the geomagnetic field will either increase in strength or decay through zero and change polarity. The history of the geomagnetic field does not imply its complete disappearance, despite creationist claims to the contrary. (R3)

From the viewpoint of the anomalist, however, the decay of this fundamental variable is very important, for we do not know why it is occurring at all and, particularly, why it is happening so fast.



Recent variations in the geomagnetic dipole moment. Observations before 130 years ago are paleomagnetic. (X1)

Is the decay of the geomagnetic field real? This question is more subtle than it appears. Geophysicists are agreed that the dipole component (presently 90% of the field) is definitely decreasing. But G.B. Dalrymple points out that the non-dipole component (presently 10%) has been increasing enough to almost compensate for the waning dipole component. In effect, the geomagnetic field seems to be becoming less and less "dipolish". Perhaps even more important is that portion of the geomagnetic field that we cannot measure directly---that part well below the earth's crust. (R14) This "hidden" magnetic energy could even be increasing!

The "young earth" claim of the scientific creationists. Scientific creationists, notably T.G. Barnes, maintain that the geomagnetic field is actually generated by a powerful electric current that was conferred when the earth was created rather than by dynamo action. In this view, the decay of the geomagnetic field is simply the consequence of this primordial electric current decreasing due to the internal electrical resistance of the planet's materials. According to Barnes, the field has been decaying exponentially with time. When the geomagnetic field prevailing 10,000 years ago is computed on this basis, using the historical trend, it turns out to be ridiculously large. The earth, then, must be less than 10,000 years old! (R2, R3, R9, R11, R13-R15, R18, R20-R24) The implications of archeomagnetism and paleomagnetism seem to have been ignored by the creationists.

G.B. Dalrymple has written a long paper refuting the claims of the scientific creationists. These claims really rest upon the assumption that a primordial electric current was created with the earth by fiat. This current is postulated because of the lack, according to the creationists, of a viable geodynamo model. Although the geodynamo model has its problems (See ESF3.), it seems to have a better chance of explaining the past ups and downs of the geomagnetic field, the field's westward drift, its transients, and the complex structure of the non-dipole field than a steadily decaying primordial electrical current. (R14) In other words, although a circulating electric current could generate the geomagnetic field, it cannot account for the field's temporal and geographical characteristics; and, of course, there is evidence that the earth's field existed over a billion years ago. (WRC)

Practical consequences of a zero geomagnetic field. The geomagnetic field for all its vicissitudes is a reliable shield against the energetic charged particles comprising solar and galactic cosmic rays and the solar wind. Long-term removal of this shield could be devastating to the biosphere. Actually, some scientists have suggested that the biological extinctions in the fossil record could have been caused by zero-field episodes occuring, perhaps, during polarity reversals. See ESB.

X2. Drift and changing structure of the non-dipole field. The non-dipole field, as characterized by maps of equal declination, equal inclination, etc. is not static. The features of these maps drift across the globe, rotate, change form, and wax and wane. Whatever generates the total geomagnetic field---the geodynamo or some unrecognized mechanism---must be able to account for these secular changes. The manifest complexity of the changing non-dipole field implies a similar complexity in the structure of the main geodynamo and, perhaps. secondary dynamos. The same is true for any other proposed mechanisms of field generation. One must admit that the motions of a fluid, metallic core could mimic the complexity of the measured geomagnetic field.

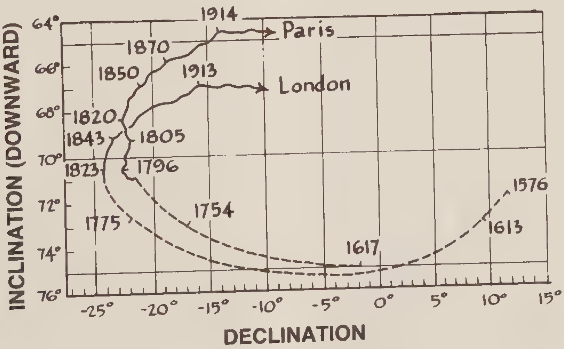
The anomaly in this situation is that we just don't know exactly how the favored dynamo model can account for all the subtleties of the field. The problem is made more difficult by the sudden changes in the panorama of the secular variations introduced in X6, below.

The westward drift of some features of the non-dipole field. Early students of the geomagnetic field soon noticed that the magnetic declination and inclination at specific locations changed rather rapidly, as shown in the accompanying graph for London and Paris. The overall effect of such changes, in recent years, is an apparent westward drift of the non-pole field. H. Takeuchi et al describe the phenomenon in the following paragraph.

"It is as though we were looking at a revolving light on the shade of which the geomagnetic anomaly has been mapped. The rate of westward drift is about 0.18° in longitude per year; at that rate, the pattern should go around the earth in approximately 2000 years. The speed of westward drift is significant. Unlike magnetic storms which arise from external causes, the large-scale geomagnetic anomalies and their westward drift must be caused within the earth. Generally, changes within the earth occur very slowly, encompassing millions and even billions of years; two thousand years is a very short time in comparison. Indeed, this is an important key to the explanation of the earth's magnetism..." (R3)

The westward drift of the non-dipole field has been ascribed to: (1) slippage between the liquid core and the mantle; and (2) wave motion of fluids in the core. Unfortunately for these appealing theories, the westward drift now seems to be confined mainly to the Atlantic hemisphere, 90°W to 90°E longitude. In this hemisphere, some features move as much as 10 kilometers per year, but in the Pacific hemisphere westward drift all but ceases. (R25)

Ephemeral features of the non-dipole field. In addition to the westward drift



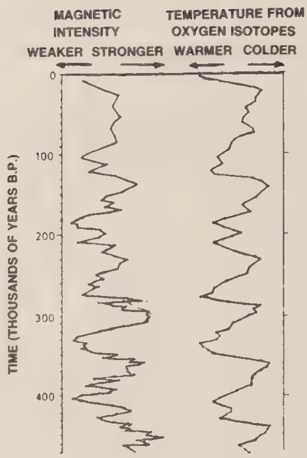
Secular variation of geomagnetic declination and inclination at London and Paris. (X2) phenomenon (geographically limited though it may be), some of the mapped features of the non-dipole field form, grow, change configuration, and decay on a time scale of hundreds of years, as one can see from historical records of the field measured at the earth's surface. As described in EZF1, J. Bloxham and D. Gubbins may have found a way to accurately map similar features deep down at the core-mantle boundary. Some of the things they have found in their analysis of about 300 years of observations are:

- Rapidly drifting flux spots in the Southern Hemisphere that drift westwards from around 90°E towards South America
- Intense static flux bundles under Arctic Canada, Siberia, and Antarctica
- Static, near-zero-flux patches under the North Pole, under Easter Island, under the northern Pacific Ocean, and possibly under the South Pole. The polar patches are surprisingly near the poles where the dipole field should be of maximum intensity. (R19, R25) Quite obviously, we are not dealing with a simple phenomenon here. (WRC)

X3. Correlation of geomagnetism and climate. Causal connections between the earth's magnetic field and climate are not easy to imagine. It is therefore understandable to find a certain reluctance among scientists to accept the correlations reviewed below.

A pioneer in searching out correlations between geomagnetism and climate has been G. Wollin. Wollin has looked at many of the variables employed in describing the magnetic field and climate to see which, if any, vary in step with one another, perhaps even with a time lag between them.

The two pertinent bodies of data are: (1) almost 300 years of direct measurements of the geomagnetic field and climate parameters; (2) paleomagnetic and paleoclimatological data stretching back for millions of years. Both bodies of data produce intriguing correlations, providing the right variables are chosen for comparison. See also EZP5-X4 for the "paleo" correlations.



A convincing correlation exists between magnetic intensity and temperature for the last 400,000 years. (X3)

The "recent" correlation. Wollin's attempt to correlate recent magnetic data with climate met with scant success until he found a link between the rate-of-change of magnetic intensity and sea-surface temperature. Further, this correlation became convincing only when a three-year delay was assumed between the increases in the rate-of-change of magnetic intensity and increases in sea-surface temperature. Again, the physical mechanism proposed is rather involved: (1) magnetic changes induce motion in the ionosphere; (2) these are coupled to the lower atmosphere and oceans in a complex feedback loop that ends with a rise in sea-surface temperature; and (3) sea-surface temperatures affect climate/weather with a three-year lag. (R10)

X4. Geomagnetic fluctuations potentially correlated with weathering processes. We have here only a weak possibility that a correlation exists, as seen, perhaps, in such geological features as concentrically banded spheroidal weathering patterns. The possible connecting mechanism is explained below by R.J. Fleisher.

"The correlation of geomagnetics with

organic weathering lies in the fact that various forms of life show a sensitivity to magnetic forces, with changes in ambientlike conditions causing involuntary modification of life functions in some species of lower life forms. Should similar effects influence microorganisms, as suggested by Sisler and Seuffle, Becker, Palmer, Bairamova and Aliev, and Blakemore, their role in the weathering regime may be sufficiently altered to cause variations in weathering products and patterns." (R5)

X5. Historical measurements of polar wandering. The subject of polar wandering will be treated in greater depth in EZP3, in connection with paleomagnetic anomalies, but it is worthwhile noting here that the positions of the magnetic poles have changed quite rapidly in the past 150 years. G.B. Dalrymple elaborated as follows.

"Secular variation results in changes in the location of the earth's magnetic, or dip, poles. The dip poles are those points on the earth where a freely suspended compass needle points straight down. The dip poles move much more rapidly than the poles of the dipole field. Today, for example, the north magnetic pole is located not at the north geographic pole (latitude 90 degrees N.), but at latitude 77.3 degrees N., longitude 101.9 degrees W. In 1831, however, when Commander James C. Ross found and claimed the north magnetic pole for Great Britain, the pole was located at latitude 70.1 degrees N., longitude 96.8 degrees W. Thus, the north magnetic pole has moved about 800 kilometers in the past 150 years." (R14)

The rapid motion of the dip poles must somehow be encompassed by the geodynamo theory; otherwise, an anomaly exists.

X6. Secular variation impulses or manetic "jerks". The major component of the secular variation of the earth's nondipole field is its westward drift. Superimposed upon the general drift are sudden accelerations on a time scale of roughly one year. Such "jerks" were discovered through the analysis of magnetic measurements from many magnetic observatories worldwide.

"Secular variation of the geomagnetic field observed at the Earth's surface has been found to undergo rapid accelerations lasting less than a few years, a much shorter duration than had previously been recognized for signals generated in the Earth's core and having diffused through the electrically-conducting mantle. One such rapid and worldwide acceleration occurred in 1969; an earlier, a less well documented acceleration apparently occurred around 1913. The identification of these events was made possible by carefully assembled long data sets from magnetic observatories around the world." (R17)

Some geophysicists have been very skeptical about the real nature of the 1969 jerk. For one thing, this magnetic impulse was not discerned everywhere. In some parts of North America, the magnetic records show nothing; elsewhere the event is not well-defined. Nevertheless, the phenomenon was very distinct in many widely separated localities. (R28, R29).

Such short-term changes were previously thought to be impossible for geodynamo-generated fields. While short-period variations in the geomagnetic field (transients) do occur, these are linked to currents flowing in the ionosphere and are, therefore, of external origin; viz., solar-generated charged particles. [These transients and magnetic storms are not considered anomalous and are not covered in the Catalog of Anomalies.] The time-scale boundary between geodynamo-created secular variations and sun-generated transients was thought to be from 4-10 years before the "jerks" were observed. (R17)

Theorists are hard put to conceive of geodynamo instabilities that would produce a magnetic jerk observable on the earth's surface through the "insulation" provided by the crust and mantle. One idea is that bubbles grow and migrate in the core. Another suggestion involves the "twisting" of core fluid as the fluid rotates and convects toward the core surface. (R26)

Changes in the pattern of secular variation also occur on a smaller geographical scale. H. Mizuno analyzed 12 years of magnetic data from 40 Japanese stations and found abrupt changes at several. These smaller disturbances did not appear to be related to one another or to the 1969 "jerk". (R28)

The earth's core, if it does constitute

the geodynamo, as almost everyone contends, is a very turbulent entity with its own "weather". It should be recognized that surface-confined geophysicists can detect only those changes that have the strength to diffuse upward through the 2900-kilometer, partially insulating crust and mantle. The geomagnetic field at the core-mantle boundary is doubtless more dynamic and disturbed than we now perceive. It could, in fact, be capable of chaotic behavior. (WRC)

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EZF3 Problems of Geomagnetic-Field Generation

Description. Theoretical and practical objections to the favored geodynamo hypothesis and other schemes that have been proposed for the source of the geomagnetic field.

Data Evaulation. Much has been written pro and con about the geodynamo theory. The bulk of the discussions in the literature, though, uncritically accept the premise that the geodynamo theory is the only physically viable possibility. Little effort seems to have been made to explore radical, speculative concepts. Rating: 2.

Anomaly Evaluation. In contrast to most entries in the Catalog of Anomalies, we deal here with theories rather than anomalous observations. The importance of establishing the source of the geomagnetic field makes it worthwhile to deviate momentarily from our concentration upon observables. The anomalies that cause geophysicists to question the geodynamo theory have already been recognized in EZF1 and EZF2. The additional "difficulties" noted below merely accentuate the seriousness of the situation. Rating: 1.

Possible Explanations. None required since the focus is on theory rather than observations.

Similar and Related Phenomena. None.

Examples

X1. The geodynamo theory. Virtually all scientists in all fields assume that the geodynamo theory is the only viable one ---and our reviews of the literature confirm this. Not that some are not uneasy about the geodynamo theory; it is the apparent lack of reasonable alternatives.

Geophysicists range in their level of confidence from J. Bloxham and D. Gubbins, who assure us that: "The basic characteristics of the geodynamo have been known since the 1950s"; (R9) to a more sobering evaluation by R.T. Merrill and P.L. McFadden:

> "Although there does seem to be a strong consensus that 'the dynamo model picture' for the Earth's magnetic field is correct, there are in fact many dynamo models, none of which has been demonstrated to work for the Earth, and each of which is incomplete in some manner or another. The problem is very difficult because, for even an approximate solution, there are several coupled nonlinear partial differential equations that must be solved simultaneously. Furthermore several of the critical parameters are effectively unknown (e.g., the viscosity of the Earth's core is still not known within several orders of magnitude). Overall, we appear to be far from obtaining a complete solution. (R7)

The problems afflicting the geodynamo theory are several. The preceding entries (EZF1, EZF2) have presented the complexities of the internally generated geomagnetic field in terms of time, configuration, and geography. Since doubts exist as to just how the simple, "basic" dipole field is generated, the situation worsens when the subtleties of the nondipole field are considered. Beyond the problems of complexity lie two additional problem areas: (1) the source of the initial magnetic field required to start up a self-excited dynamo; and (2) the source of the energy that keeps the geodynamo going once started.

The initial magnetic field A self-excited dynamo requires a separately supplied magnetic field to get it started. The separate field need not be large---just enough to "prime the pump", so to speak. Two suggested sources of this field are: (1) thermoelectric currents in the mantle; and (2) the solar magnetic field, which extends throughout the solar system. (R1)

The geodynamo's source of energy. The hypothetical geodynamo needs about 8 x

10^8 watts of power to keep it operating at its present level. (R5) This power required to sustain the geomagnetic field eventually manifests itself as heat in the liquid, electrically conducting core. Opinions differ as to the source of this power. Initially, in the geodynamo theory, this power is expressed in the motion of the core fluid (convection, turbulence, etc.). Several ways have been suggested for setting the core fluid into motion:

1. Heat from disintegrating radioactive materials. Unfortunately, meteoric iron, which we would expect to be similar in composition to the earth's liquid core, does not contain enough radioactivity to run the geodynamo. (R1)
2. Relict heat from the earth's formation. G.B. Dalrymple states that, over the past 3 billion years, a temperature drop of only 100°C in the core would have been sufficient to keep the geodynamo going. (R5)
3. The earth's rotation, as manifested in precessional motion and convection in the core. (R1, R2, R5)
4. Seismic energy communicated to the core. (R3)
5. Gravitational energy supplied through chemical differentiation as heavier materials sink and lighter ones rise. (R4, R5, R10)
6. Heat evolving from liquid-to-solid phase changes. (R1)
7. Impact energy from asteroids, comets, etc. Obviously, immense impacts would be required to transmit sufficient energy to the deep core. (R8)

Today's general consensus seems to be that most of the geodynamo's power is derived from heat (both relict and radioactive) and the earth's rotation. However, all of the listed possibilities, except #7, may be involved.

X2. Other mechanisms for generating the geomagnetic field. Some creationists claim that the geomagnetic field arises from a primordial electrical current still circulating in the core. (See EZF1.) Since this scenario implies an earth younger than about 10,000 years, it is not taken seriously in scientific circles.

In considering other possible sources of the earth's field, it should be reemphasized that permanently magnetized geological material cannot be considered because: (1) core and mantle temperatures higher than the Curie point preclude permanent magnetization; and (2) the dynamic characteristics of the geomagnetic field are incompatible with solid, permanent magnets, unless they were somehow entrained in a cold slurry or some other improbable system.

The only other possible source for the field mentioned in the literature surveyed is thermoelectricity generated by unidentified thermoelectric couples in the earth. (R1) No elaboration of this idea has yet been found.

The seeming absence of other acceptable alternatives to the geodynamo theory explains its popularity. The only path remaining is to postulate some still unrecognized physical phenomenon. Thus, we arrive at an impasse. The geodynamo theory possesses several grave faults, but no reasonable substitutes exist. (WRC)

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EZP PALEOMAGNETISM

Key to Phenomena

EZP0 Introduction

Paleomagnetism differs from what is often called "terrestrial magnetism" in that it relies upon magnetic measurements made on datable rocks, sediments, and human artifacts. Because paleomagnetism uses the intensities and directions of remanent magnetism in volcanics and sediments, which may have undergone chemical and physical alterations as well as changes in position and orientation, many opportunities exist for errors in measurement and interpretation. In fact, a few scientists have expressed doubts about the overall validity of paleomagnetism. Nevertheless, paleomagnetism has helped revolutionize the earth sciences, especially in plate tectonics where it has provided vital age correlations in deep-sea drilling programs.

In addition to sketching some of the problems of paleomagnetism, this chapter treats three other facets of paleomagnetism: (1) The reality, nature, and scientific significance of paleomagnetic excursions and reversals; (2) The determination of ancient magnetic poles (paleopoles), their purported tracks, and their significance in plate tectonics and the expanding earth theory; (3) The manifold correlations between polarity reversals and other geological, geophysical, biological, and astronomical phenomena.

EZP1 Problems in Measuring and Interpreting Paleomagnetism

Description. Factors in the collection, measurement, and interpretation of paleomagnetism that can, in principle, undermine the validity of conclusions made in this field. Most factors, such as the distortion of sea-bottom sediments by slumping, the lack of an acceptable theory for reversals of the geomagnetic field, and the chemical alteration of NRM are not anomalous per se, but rather they are contributors to a vague lack of confidence in paleomagnetism in some circles.

Data Evaluation. Paleomagnetism has attracted the efforts of many scientists in recent years and, in addition, there has been much soul-searching concerning its basic validity. Consequently, the literature here is large---pro and con. Rating: 1.

Anomaly Evaluation. As stated above, we do not really deal with true anomalies here. Instead, this is a cautionary section interjected in this part of the Catalog to advise readers to be wary of inflated claims.

The first concern of paloemagnetism is obtaining samples that truly reflect the ambient magnetic field at the time of deposition. Just the process of coring a sediment can distort the sample, and of course the sample could have actually been disturbed by slumping and other natural forces millions of years ago. Geophysicists take such factors into account as well as they are able. In addition, some sediments are simply not good recorders of the geomagnetic field; some even exhibit heterogeneous NRM properties. Finally, scientists must always ask how meaningful the NRM of a sample is given the rapid changes in declination observed in historical times.

The frequent reversals of the geomagnetic field during past eons is usually assumed to be a well-demonstrated phenomenon. In X2, we ask if a viable theory theory exists to explain field reversals, assuming they really occurred. Then, in X3, we explore phenomena that may change the NRM of a sample independently of the field prevailing at the time of deposition, such as self-reversal and the chemical alteration of NRM.

No anomalies exist to be evaluated here---we present only caveats.

Possible Explanations. None required.

Similar and Related Phenomena. It is common in science for exciting paradigms to blind their proponents into ignoring or overconfidently "correcting for" recognized problems in methodology.

Examples

X0. Introduction. The earth's rocks acquire natural remanent magnetization (NRM) in two important ways: (1) thermal remanent magnetization (TRM), in which rocks "lock in" the ambient magnetic field as they cool through the Curie point; and (2) detrital remanent magnetization (DRM), in which magnetic grains are aligned with the ambient magnetic field as they settle during the formation of sediments. As we shall see in X3 below, there exist several other ways in which NMR can be induced or created. Some of these alternate mechanisms may, on occasion, distort paleomagnetic measurements.

One of the leading figures in geochronology and paleomagnetism, G.B. Dalrymple expressed, in the following paragraph, the confidence the scientific community in general has in paleomagnetic measurements.

"By collecting oriented rock samples in the field and measuring their magnetism with laboratory instruments, scientists can determine the characteristics of the magnetic field at the place and time that the rock formed. Note, also, that because the magnetic field is a global phenomenon, its polarity at a given time can be determined by measurements from a single rock anywhere on earth. Certain factors, such as lightning and chemical alteration, can interfere with the recorded magnetic information in both igneous and sedimentary rocks, but scientists have devised extensive laboratory tests and procedures to identify and, in most cases, erase anomalous components, so that the true magnetic information can be extracted and the unreliable results identified. Paleomagnetism is a highly reliable and universally acknowledged way of reconstructing the history of the earth's magnetic field." (R12)

One purpose of the Catalog of Anomalies is the identification of weaknesses in well-established paradigms and the measurements that went into their formulation so that they can be improved. In the case of paleomagnetism, despite the above quotation, it seems that a few problem areas remain.

X1. Measurement problems in paleomagnetism. Measurement difficulties commence with the garnering of samples and continue through their preparation, measurement, and interpretation. In the September/October 1982 issue of Mosaic, D. Mulholland summarized the situation as follows.

"The types of rock found most useful for paleomagnetic studies include lavas, magmatic intrusions of molten rock into fractures in existing solid rock, petrified sediments in old lake and ocean bottoms, and newly created crust. Each of them has unique advantages, but none of them is perfect. Some give continuous records, others accurate intensities, yet others unambiguous directions. None gives all three.

"For example, sediments are collected by drilling, and a bad technique will disturb the orientation of the core sample. Variable erosion and sedimentation rates can falsify the record, and the magnetic properties are sometimes disturbed by oxidation. At the University of Minnesota, Subir Banerjee studies lake sediments because he considers ocean sediments to be 'hopeless.' Miami's Chris Harrison, on the other hand, agrees that some ocean sediments are hopeless, but 'other ones are very good recorders and they are easy to spot.'

"On land, lavas give fine intensities but are extremely episodic. As Michael Fuller, of the University of California at Santa Barbara, notes, "We don't know if a particular sequence of lava flows all came out in a month or took a few years or a few thousand years.' Intrusions of magma from the earth's interior, which cool slowly beneath the earth's surface, provide continuous records of the field, but their magnetization is sometimes hard to interpret, and the field's intensity is sometimes hard to measure." (R11)

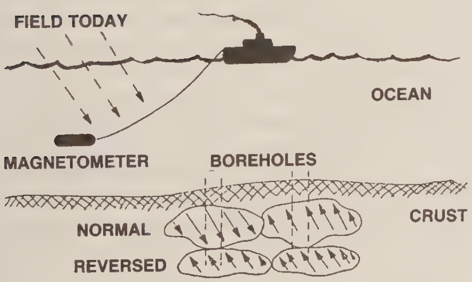
Mulholland's paragraphs are not as reassuring as that of Dalrymple in X0.

Specific problems with natural remanent magnetization in sediments and sedimentary rocks. (1) Ocean sediments are subject to deformation by erosion, slumping, turbidity currents, earthquakes, and other forces. The ocean bottom is, in fact, a dynamic place. It is often difficult to be sure that the sediments being sampled have not been disturbed after they were magnetized. (2) The coring operation may also disturb the orientattion of the sample and even contaminate it with extraneous material. The twisting of the core is often blamed for sudden, unexplained changes in the magnetic direction. (3) Core shrinkage while drying may also change the direction of magnetization. (4) Ocean-bottom currents may change the alignment of the magnetized particles over wide areas. (5) Burrowing organisms can disrupt the sediments in unpredictable ways. (R15) The practitioners of paleomagnetism naturally try to correct for such perturbations.

Ancient magnetic declinations are difficult to estimate. From EZF2, we know that compasses rarely point to true north. Magnetic declinations can be large and may change rapidly in unpredictable ways. Therefore, even if a sample's NRM accurately reflects the actual geomagnetic field prevailing at the time of deposition, one cannot pinpoint true (geographic) north with assurance.

NRM can be both normal and reversed in the same sample. Abstract. "Seventeen years ago the coexistence of both normal and reversed natural remanent magnetizations (NRM) was found in the early Pleistocene or late Pliocene basaltic lava flow at Kawajiri-misaki, Yamuguchi Prefecture, Southwest Japan. It was once understood that the NRM was due to a reversed geomagnetic field at the time the lava flows erupted, and normal NRM was neglected because of its instability. However, the coexistence of both normal and reversed NRM, even in so small a portion of the lava flow, has remained a mystery. Was the earth's magnetic field reversed at that time, or did self-reversal take place? In this report, the author proposes a self-reversal mechanism as a solution to this mysterious phenomenon. He also considers that the unstable NRM might be usable in some cases as a paleomagnetic 'fossil' rather than the stable NRM which usually seems to be a good indicator of the earth's magnetic field in the past." (R5)

Deepsea magnetic stripes can be heterogeneous. Instead of revealing neat, uniform, magnetized stripes on the ocean floor, cores from drilling programs suggest that the ocean floor is actually a jumble of separate, differently magnetized regions, each meters in extent and each displaying different polarities. (See figure.) (R22) The ship-towed magnetometers responsible for delineating the ocean-floor stripes really record only the average NRM of the regions they pass over. If this reported heterogeneity is widespread, it could jeopardize the entire fabric of sea-floor spreading and plate tectonics. (WRC)



Ship-towed magnetometers sometimes indicate strong reductions of field intensity in magnetic anomaly regions. Deep drilling at such sites reveals the existence of localized hodgepodges of rocks with normal and reversed polarities. (X1)

X2. Mechanisms for explaining reversals of the geomagnetic field. When measurements of NRM in continental and sea-floor deposits showed that a large fraction (about half of the samples) displayed reversed polarity, earth scientists were initially taken aback. At that time, it was astounding that the planet's field could be reversed---and often rather suddenly on the geological time scale! But the data were and are quite convincing, even allowing for the sampling and measurement problems mentioned in X1. Today, reversals of the geomagnetic field are a keystone in the edifice of paleomagnetism, particularly in the area of sea-floor spreading.

The convincing evidence of field reversal forced a search for reasonable physical mechanisms. Most scientific work has focussed on modifications of the hypothetical geodynamo, but wilder theories involving crustal slipping and even outright flipping of the entire planet can be found in the fringe literature and, on rare occasions, the mainstream scientific journals.

Modifying the geodynamo for reversals. The picture of the magnetic field at the core-mantle boundary provided by the method of J. Bloxham and D. Gubbins (See EZF2.) has provided some tantalizing hints about how a field reversal "might" occur. The moving "patches" of reversed flux seen (through a mathematical algorithm) on the core surface can, in principle, lead to the decay of the geomagnetic field we perceive at the planet's surface. The reversed flux of patches simply opposes and cancels part of the normal dipole field. These patches are probably created by thermally driven fluid upwellings in the molten core. In a theory proposed by D. Gubbins, the patches of reversed flux may sometimes increase in size and strength enough to completely cancel out the dipole field and then drive the externally perceived geomagnetic field into a reversed state. The patches are likened to sunspots, which are magnetic storms on the sun that are associated with the reversal of the sun's magnetic field every 11 years or so. (R18, R19) Extending the earth-sun analogy, one might expect reversals of the geomagnetic field to be crudely periodic like the sunspot cycle. (WRC)

A catastrophic theory. In 1978, P. Warlow's paper on "pole flipping" was published in the Journal of Physics. His Abstract follows.

"The enigma of geomagnetic reversals and their apparent link with other phenomena, such as faunal extinctions, is shown to be explicable by treating these reversals as a relative rather than an absolute effect.

"Instead of reversing the magnetic field, it is suggested that a reversal of the Earth itself in a particular manner is sufficient to account for the behaviour of the field in detail during a reversal, and for explaining the links with the various other phenomena. It is shown that a wide variety of data is compatible with this hypothesis, not only from modern geological and related investigations, but also from astronomy and from ancient sources." (R8)

E. Crew has provided a capsule description of Warlow's thesis.

"Warlow claims that at recognised intervals between a tenth of a million and one million years the Earth is disturbed by cosmic events such as the near miss of a body the size of the Moon, or a small planet, on an erratic orbit. On each occasion the disturbances may occur several times within a century or so.

"The powerful tidal forces and possibly electrical and magnetic interactions during such an event impose a turning force on the axis of the rotation of the Earth. The gyroscopic action is assisted by the equatorial bulge of the Earth, so its axis normally tends to point to a fixed direction, except for the slow precession wobble caused by the equatorial bulge responding to the pull of the Sun and Moon. If a cosmic event produces a secondary turning effect large enough to deflect the Earth's rotation axis more than 90°, it will tend to stabilise in the reverse direction. The Earth turns upside down---and this can happen in one day!

"The important feature of Warlow's theory is that when the Earth inverts, its spin, viewed from the outside remains in the same direction. To a person on the surface of the Earth however, its direction of spin would be reversed and he would see the Sun rise in the West.

"The magnetic field direction and spin direction are associated, so both would be reversed in about the same time. The tidal forces associated with this axial deflection and the effect of the reversal of rotation in producing drastic changes to the established patterns of circulating currents in the seas and in the atmosphere would explain the major disturbances to life and climate." (R31)

Obviously, Warlow's thesis has Velikovskian overtones. His theory has had little impact on mainstream geophysics.

In his Introduction, Warlow mentions two other radical theories of geomagnetic field reversal: (1) The idea that the earth possesses a net electrical charge, which, because of the earth's rotation, generates a magnetic field. In this hypothesis, the field is reversed when the sign of the electric charge on the earth is reversed by some unspecified phenomenon. (2) The concept that the earth has a two-zoned liquid core, one zone producing a field of one polarity; the other, the opposite polarity. These two zones, again for unspecified reasons, alternate in dominance. (R8)

As customary in the Catalog of Anomalies, we only mention theories briefly, preferring instead to concentrate upon the anomalous data.

X3. Phenomena that may distort paleomagnetic measurements.

The property of spontaneous self-reversal. During the 1960s, some scientists doubted whether rocks found with NRM opposite to that of the ambient magnetic field actually acquired their magnetism from ancient reversed fields. A major reason for these doubts was the surprising discovery of self-reversing minerals; that is, minerals which under some conditions could spontaneously reverse their magnetic polarities. (R2) That this phenomenon might undermine the whole discipline of paleomagnetism was evident in 1967, when two Japanese scientists reported that three out of eight specimens of basalt obtained from deep-sea mounts exhibited self-reversal properties under certain conditions. (R4) By 1970, however, such worries had subsided because, on a worldwide basis, rocks possessing the property of self-reversal were found to be rare---too rare to compromise the concept of sea-floor spreading, which depends heavily upon the pattern of normal and reversed magnetic stripes adjacent to the mid-ocean ridges. (R12)

Titanohematite was one of the minerals found in the rare self-reversing rocks. In 1985, titanohematite was found to be more common that originally thought. S. Weisburd reported as follows in Science News,

"Titanohematite has recently been found to be the dominant magnetic mineral at three sites---a lava field and two sedimentary basins---indicating to the scientists who found it that it may not be as rare as people think. These findings in no way challenge the field-reversal theory, but they could complicate the analysis of the magnetic orientations of rocks that help scientists date lava beds." (R14)

At present, no one seems unduly disturbed by the titanohematite problem, because everyone assumes that it is still rare, although not as rare as previously claimed. Nevertheless, it should be worrisome that titanohematite was unexpectedly found to be an important mineral in two large sedimentary basins. This fact alone should direct more attention to this matter. (WRC)

The possible role of magnetostriction in paleomagnetism. Can the application of pressure to magnetized rocks change the intensity and/or direction of their NRMs? J.W Graham was led to investigate this potential challenge to the field of paleomagnetism by the "...grossly scattered magnetization directions noted in various surface samples of the Karroo dolerites." In his 1956 paper on this subject, Graham also pointed to the great difficuties encountered in interpreting the confusing NRMs of the Trenton and Onondaga limestones of New York State. He wrote, "In summary, the findings in these rocks are in gross conflict with currently held views (magnetostriction excepted) or common sense, or both. It seems that something must be added to our knowledge of rock magnetism," In this vein, it is worthwhile reproducing Graham's Abstract.

"The role of magnetostriction in the problem of rock magnetism has heretofore been neglected. Based on some experimental observations and on reconsiderations of well-known factors affecting rocks, the conclusion is reached that magnetostriction may figure prominently in establishing the directions of magnetization observed in many cases. Therefore, the practice of interpreting meager magnetic data in terms of polar wandering and continental drift can be in error." (R1) Here we have another serious challenge to the integrity of paleomagnetism.

Some 16 years later, S.E. Mussett reviewed the magnetostriction problem, beginning with a reference to Graham's laboratory experiments.

"He [Graham] went on to show in the laboratory that uniaxial stress, equal to the weight of a column of rock half a kilometre high, changed the intensity of magnetization of most rocks, by up to a quarter or more, with accompanying directional changes. This stimulated research in a number of laboratories in the late 1950s, with the conclusion that though stress could affect magnetization it affected only the softer components and is roughly equivalent to applying an alternating field. With the development of routine 'cleaning' techniques it ceased to be a bogey and interest in the effects of stress largely faded, with the exception of its possible use as a harbinger of earthquakes." (R10)

In sum, then, the effects of magnetostriction on paleomagnetic measurements are now routinely "corrected for" and given little further consideration. In this Catalog of Anomalies, it is essential to flag such situations where faith in a prevailing paradigm is so strong that disturbing data may be filtered out. (WRC)

Interestingly enough, Mussett also mentions is his paper the curious absence of magnetic anomalies over the ocean floor as the ocean trenches are approached; that is, the alternating bands of normal and reversed magnetic stripes disappear as the ocean-floor "conveyor belts" near the areas of subduction. Could intense pressures in these regions account for this phenomenon? (R10)

If so, magnetostriction does play a significant role in paleomagnetism. Further, we still have the already mentioned paleomagnetic problems with the Karroo, Trenton, and Onondaga formations---and doubtless many other formations not yet encountered in our literature searching. (WRC)

Geochemistry and paleomagnetism. It

must be somewhat embarrassing to the proponents of paleomagnetism to have to contend with still another complication, in addition to self-reversal and magnetostriction. Here, we report on the complexities associated with the role of geochemistry in altering the NRM of a sample or even helping to create the NRM in the first place. Once again the validity of all of paleomagnetism is at stake here.

After reviewing the evidence supporting the discipline of paleomagnetism, R.L. Wilson, back in 1965, set out the problem of sample polarity as correlated with oxidation state.

"The reader may now be convinced that former reversals of the Earth's magnetic field are already demonstrated beyond fear of contradiction. If so, he must now face, as those working in this field have had to do, a very awkward discovery.

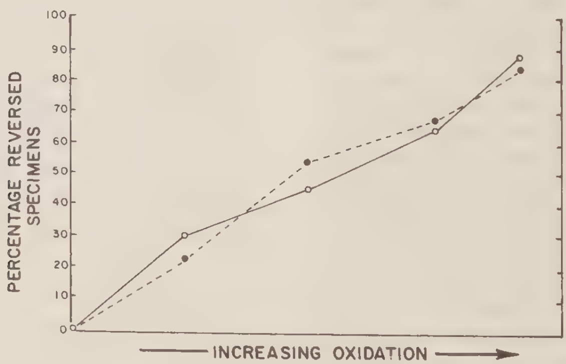
"Last, year, Dr. J.M. Ade-Hall, then at Imperial College, London, reported that, at high magnification under the microscope he could see very obvious chemical and structural differences between normally and reversely magnetized lavas from the Isle of Mull, Scotland. We were unable to find any definite corresponding differences in the magnetic properties of the same lavas. The geological setting of these lavas was very complex, and so the interpretation was doubtful. But subsequent work by Prof. P.M.S. Blackett and by ourselves has brought to light several other cases of chemical differences between normally and reversely magnetized lava sequences from various parts of the world.

"With one exception, they have so far indicated the same statistical trend---that reversely magnetized lavas are more highly oxidized than normal ones. No differences in the distribution of other elements involved in the magnetic minerals, notably the relevant metals, iron and titanium, have been observed. I should add that the evidence suggests that this state of oxidization was achieved during the intial cooling of the lavas. It does not seem to have been a slow, subsequent phenomenon (due to weathering for example).

"The most interesting lava sequences we have so far investigated are the Columbia Plateau Basalts from America, collected by Dr. N.D. Watkins. Sets of lavas from eleven different sites have shown a remarkably clear relation between natural magnetic polarity, the state of oxidation and the magnetic properties."

.....

"The dilemma is this: if one accepts the evidences for field reversal, how can one explain the statistically different chemistries of normal and reversed lavas in some sequences? If, on the other hand, one accepts the hypothesis of self-reversal to explain the chemical differences, how can one explain away the variety of evidences for field reversal? Nor is the answer possibly sometimes field reversal and other times self-rever-



Basalts from the Columbia Plateau show a clear relationship between the proportion of reversely magnetized specimens and state of ionization. (X3) sal, for the two conflicting kinds of evidence have occurred in the same lava sequence, in two instances of different age and geographical position.

"Unless some of the evidence is entirely misinterpreted, or unless the chemical correlation with magnetic polarity is pure coincidence in several cases, one seems forced to conclude that the ancient magnetic field really has reversed its polarity, and that the state of oxidation of lavas can, for an unknown reason, be connected with the polarity of the magnetic field, because one is hard pressed to imagine what physical connection can possibly exist between the polarity of the Earth's magnetic field, and the state of oxidation of lavas which became magnetized in that field." (R2)

Although Wilson does not claim that the correlation between polarity and oxidation state is universal, it is necessary to state more definitely that the phenomenon is not consistent. For example, basalts from the Canary Islands reveal no correlation whatsoever between polarity and oxidation. (R6)

Not only is oxidation state correlated, in some instances, with magnetic polarity but so also are other rock properties, as brought out by P.J. Smith.

"What then are we to make of the correlations between polarity and other properties which have been observed in several sets of rocks? Differences in petrographic texture, grain size and the form of olivine grains have been observed between normal and reversed German basalts; excess TiO_2 has been discovered in reversed basalts from southern Siberia; the Fe_2O_3/FeO ratio is greater in some reversed Armenian Quaternary lavas than in the corresponding normal ones; and reversed lavas from Kazakhstan (USSR) and reversed metamorphic rocks from the Adirondack mountains (USA) are more highly oxidized than the respective normal samples. The fact is that, rightly or wrongly, proponents of field reversal have tended to dismiss these and a few other examples as insignificant on the grounds that there are so few of them and that these properties correlating with polarity are too varied to enable generalizations to be made. (Most of them, however, seem to imply higher oxidation states for reversed rocks.) They were interesting examples which hopefully could be put down to coincidence or local conditions, or which were, at worst, isolated cases of possible (but unproven) self-reversal that did nothing to disprove the predominance of field reversal.

"But during the last few years the number of well documented correlations has shown an embarrassing increase, so that it is no longer possible to dismiss this type of evidence so lightly." (R7)

Smith continued his review by listing three possibilities: (1) The correlations are merely fortuitous and field reversal explains everything; (2) Field reversals did not occur and all reversed polarities are the consequence of self-reversal; (3) "The third explanation, which at first seems as unlikely as the other two, is that field reversal is the cause of the reversely magnetized rocks, but that the observed correlations are nevertheless real and significant." In other words, there may be a connection between the polarity of the field and the oxidation state of the lavas, even though the geomagnetic field is strongly believed to originate in the core and the lavas in mantle. Smith characterizes this thought as "incredible," but thinks some thought should be devoted to this possibility. (R7)

One more aspect of this delightfully complex nest of anomalies is the possibility that the mineralogy of a sample may determine whether the specimen, when exposed to a normal field. is magnetized in the normal or reverse direction. This phenomenon is seems somewhat different from ordinary self reversal. F. Heller et al have reported as follows.

Abstract. "One of the fundamental principles of palaeomagnetism and rock magnetism states that the direction of natural remanent magnetization (NRM) is acquired parallel to the applied field. However, ferromagnetic mineral phases with complex microstructures may violate this rule and produce a magnetization which is antiparallel to the direction of the external field." Heller et al described how pyroclastics from the 1985 eruption of Nevado del Ruiz, in Columbia, exhibited self reversal during the actual acquisition of NRM. (R16) This might be called "instantaneous" self reversal as opposed to "delayed" self reversal discussed earlier. Heller at al put it this way: "The major significance of the self-reversal observed in the Nevado del Ruiz

1985 pumice, however, lies in the clear evidence that this mineralogical mechanism has indeed controlled the polarity of the NRM when the rock formed." (R16)

An initial assumption of paleomagnetism was that a rock's magnetism was derived from the ambient magnetic field existing during its formation. In recent years it has been found that many Paleozoic rocks acquired their NRM through chemical alteration processes that acted long after the rocks were deposited! The significance of this phenomenon has been noted by R.L. Reynolds.

"During the past eight years, however, evidence has accumulated that the remanent magnetization of many carbonate sediments was not acquired at the time of deposition, thereby invalidating some previous interpretations of the palaeomagnetic data." (R25)

In R25, Reynolds described the work of D. Suk et al, who were investigating the conversion of pyrite to magnetite via the action of crustal fluids. Suk et al believe that the NRM of the chemically altered rocks is probably that of the ambient field prevailing during the conversion of pyrite to magnetite. They admit, though, that they have not yet examined the effects of such factors as temperature and tectonic stress (magnetostriction again). (R25)

As if paleomagnetism was not already complex enough, recent laboratory observations of electrochemical cells with magnetometers add another dimension to NRM and field reversals. We do not know the significance of the following observations, but we recognize that electrochemical cells may well exist in the earth's crust ---perhaps in the mantle and core as well! The following paragraph deals with work being performed at MIT by J.G. Bellingham and M.L.A. MacVicar.

"One interesting and surprising property of electrochemical cells was discovered by accident. Normally, the magnetometer scans each cell as the cell moves horizontally beneath the magnetometer. During one run, the researchers left the cell in a single position for a long time while the magnetometer was still on. After 20 minutes or so, the magnetic field strength began to drop. 'It was very dramatic to watch this field collapse,' says MacVicar. After about a minute at zero, the magnetic field grew larger again but in the opposite direction.

"The researchers discovered that such reversals occur over and over again at irregular intervals. This implies that the corrosion currents responsible for the magnetic field can change direction. A small piece of metal surface seems to be able to switch polarity and behave as either a cathode or an anode while corrosion occurs." (R17) Could the earth be a large electrochemical cell or a group of such cells? (WRC)

Magnetofossils. Many organisms from bacteria to birds can synthesize magnetite, presumably for use in navigation. In geology, biogenic magnetite becomes important when it accumulates in sediments in grains termed "magnetofossils". Magnetofossils have been found in various deep-sea sediments and in carbonate rocks from several geological periods. (R23)

In the upper layers of soil, which are magnetized many times more strongly than deeper layers, magnetic bacteria supply part of the magnetite, with abiogenic processes providing the remainder. (R21, R24)

We mention the bilogical production of magnetite here, because it is possible that living bacteria in old sediments and porous rocks may distort the NRM frozen in when the sediments were initially deposited, by aligning themselves with the ambient field at the time they were alive. However, we know of no research that supports this idea. (WRC)

Lightning. As already mentioned in EZC2, lightning-induced currents can locally magnetize rocks and thus distort NRM measurements. The effects of lightning can usually be recognized and compensated for.

Mainstream science's concern over our ignorance of the processes that create magnetized sediments. In 1990, a special issue of the Journal of Geophysical Research presented sixteen papers on the various problems associated with sedimentation. In their Introduction to this issue, S.P. Lund and R. Karlin made the following statements that are quite pertinent to problems with the magnetization processes raised earlier in this section.

"Some of the processes are relatively well-understood; for example, the physical process of alignment of detrital magnetic grains during initial deposition which is termed depositional or post-depositional remanent magnetization (DRM or PDRM). However, other components of the sedimentary magnetization process are only beginning to be appreciated; for example, the effect of burial compaction on magnetic grain alignment or the role of biogeochemical processes which may alter an initial DRM/PDRM soon after deposition by the formation of magnetic minerals (authigenesis) or the alteration of existing magnetic phases (diagenesis).

.....

"In ancient sedimentary rocks, there is increasing evidence that primary remanence carriers can be altered and new magnetic minerals can be produced by metasomatism associated with brine and hydrocarbon migration. Recognition of such chemical remagnetization events is very important to assessing the reliability of apparent polar wander paths and the direction and amount of terrane movement." (R28)

X4. Questioning the basic assumptions of paleomagnetism. A.A. Meyerhoff, an outspoken critic of plate tectonics, has also doubted the fundamental tenets of paleomagnetism. Since plate tectonics owes its present exalted position in large part to paleomagnetism, Meyerhoff's interest here is not surprising.

The three major assumptions questioned by Meyerhoff are: "(1) The dynamo theory of the earth's magnetic field is essentially correct; (2) The axial dipole predicted by the dynamo theory and known to characterize the earth's present field is applicable for past geologic time; (3) The magnetic pole has coincided approximately with the rotational pole through geologic time." (R27)

Although Meyerhoff elaborates on all three of these assumptions, as well as several lesser ones, we here quote only his comments on the third.

"The present magnetic axis is tilted 11°-12° to the rotational axis. Hence no a priori reason exists for assuming that both poles coincided in the past. The validity of this objection usually is dismissed by magneticists on the grounds that physical theory (i.e., the dynamo theory) predicts alignment of the geomagnetic field along the axis of rotation. How can an unproved "theory" be used to predict anything---especially in the past?" (R27)

A modern answer to this criticism is that the main dipole field is aligned with the axis of rotation, and that the non-dipole field skews the overall geomagnetic field by the 11° or so that we observe. (WRC)

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EZP2 Anomalous Excursions and Reversals of the Geomagnetic Field

Description. Excursions of the geomagnetic field (including reversals) that are: (1) very recent; viz., within historical times; (2) very localized geographically; (3) very rapid; (4) periodic; or (5) follow anomalous scenarios. All such factors become anomalous when they cannot be accommodated by the geodynamo theory.

Data Evaluation. Paleomagnetism has been a very popular subject of scientific research since the 1960s. There exists a large professional literature. Rating: 1.

Anomaly Evaluation. To begin with, all excursions and reversals are anomalous in the sense that we do not know precisely how the geodynamo produces such changes or why they are initiated. The pressure on the geodynamo theory becomes more severe if, for example, the reversals are periodic, because then either an internal periodic mechanism must be found or some periodic extra-terrestrial stimulus must be identified. If the excursion or reversal progresses too rapidly, unrealistically rapid motions of core fluid are implied. Further, the geographical localization of some excursions and tracks of virtual geomagnetic poles cannot be easily encompassed by the geodynamo theory. Generally speaking, excursions and reversals seriously challenge geodynamo theory. Rating: 1.

Possible Explanations. Since the geodynamo has no important competitors, we must assume that the fluid character of the earth's core, which allows complex dynamic motion of electrically conducting liquid, can somehow account for all observations.

Similar and Related Phenomena. All EZF and EZP.

Examples

X1. Recent anomalous excursions of the geomagnetic field. According to mainstream theory, the earth is presently in the Brunhes normal polarity interval, as it has been for the past 690,000 years or so. Within the Brunhes interval, there have been several significant excursions of the field, including claims for short-lived reversals. This "fine structure", assuming it survives scientific scrutiny, suggests that the geomagnetic field is highly volatile and geographically variable. These phenomena complicate attempts to come up with an acceptable model for the geodynamo.

Archeomagnetic measurements of recent field excursions. Measurements of bricks, pottery, and other clay artifacts provide a rough picture of geomagnetic field intensity over the last 10,000 years.

In 1970, S.P. Burlatskaya published a compilation of archeomagnetic data covering the range from 6500 BC to 1960 AD. Most of his data came from the USSR and nearby countries. His Abstract follows.

"The results of measurements of geomagnetic field intensity are summarized for various points on the surface of the earth. These results are presented in the form of two smoothed curves, obtained from averaging over 500 and 50 years. The result of the first averaging reveals a monotonic pattern of variation of this element with a period of about 7000 years. The second averaging shows a cyclic variation, superposed on the first, with cycles of a duration of about 200-600 years." (R3) The short-term periodicity is surprising. See X2. (WRC)

More recently, W. Quing-Yun et al gathered similar data for Chinese pottery dating from 6000 BC. Their analysis also shows that the recent geomagnetic field has not followed a simple trend, such as that mentioned in EZF1.

Abstract. "Past values for the geomagnetic intensity may be obtained by laboratory analysis of the thermoremanent magnetization carried by clay baked in ancient times. From global averages of such determinations it is commonly accepted that the intensity in any given region went through a broad maximum about 2,000 years ago, reaching a level about 50% higher than at present. Here we present results obtained from a wide range of Chinese pottery, spanning the interval from 4000 BC to the present, indicating that the field behaviour was more complex. The intensity was high between 1500 and 1000 BC and again in the first half of the first millennium AD. Comparison with results reported for Western Asia, Egypt and Crete suggests that these high values are due to non-dipole disturbances in the geomagnetic field, consistent with long-term records of the cosmogenic radioisotopes ^{14}C and ^{10}Be." (R40)

While the two studies reported above are fairly consistent with one another, archeomagnetic results from Italy and Greece indicates a field reversal during historical times. A paragraph from C.J. Ransom's 1973 article in Nature elaborates.

"In 1896 Giuseppe Folgheraiter made studies of the Attic (Greek) and Etruscan vases of various centuries, starting with the eighth century BC. The observations were made on clay fired in kilns. The position of the ancient vases during firing is not known. They were fired in a standing position, as indicated by the flow of the glaze. The magnetic inclination of the magnetic dip of the iron particles in the fired clay indicates the nearest pole during the time of firing. His conclusion was that in the eighth century BC the Earth's magnetic field was reversed at least in Italy and Greece." (R56)

It seems unlikely that the geomagnetic field could have been reversed in Italy and Greece but not in the USSR and China. One is tempted here to question archeomagnetic techniques before concluding field reversals can be limited geographically. (WRC)

Paleomagnetic excursions 10,000 to 50,000 years ago. Using radiometric and other geological dating methods, geophysicists have identified other field excursions at about 12,500 BP and in the intervals between 15,000 and 20,000, 24,000 and 25,000, 28,000 and 30,000, and 38,000 and 40,000 years before the present. (R14) Of these, we select the one that occurred about 12,500 years ago---the so-called Gothenburg Excursion---for elaboration. R.W. Fairbridge, who investigated this event to see if it was associated with climate changes, had the following to say about it.

"I decided to test this idea in connection with the Gothenburg Excursion, the youngest well-documented geomagnetic event in the geological record. Morner and Lanser have shown this episode to have been short-lived, only 13,750-12,350 yr b.p., and Creer et al on the cores from Lake Erie, but with less precise dating, identified the excursion only to within 14,000-11,000 yr b.p. The global nature of this magnetic disturbance is indicated by other dates from the Gulf of Mexico, Japan, France and Australia, and often correlated with the poorly dated 'Laschamp' Event." (R57; R58)

See also R60, where the Gothenburg Excursion is classified as a complete reversal of the field.

Another reversal mentioned in the literature, but dated only as occurring during the last glaciation, was identified in Icelandic rocks. It is possible that this reversal may be another indicator of the Gothenburg Excursion. In any case, it reveals some of the problems encountered in the field.

Abstract. "Clear evidence of a reversed magnetic polarity event has been found in subglacial picritic lavas in the neovolcanic zone just south of Thingvallavatn in southwestern Iceland. The outcrops are poorly exposed in scree at the top of a small ridge which lies about 2 km east of the axis of post-glacial volcanism in the area. The reversed material is about 30 m thick, and it lies on top of normally magnetized pillow lavas which show some olivine settling.

.....

"The two directions [of magnetization] indicate the presence of two distinct cooling units separated by sufficient time to allow significant secular variation. The geographic distribution of samples allows such a separation, and the possibility of petrological differences is being investigated. The shallowly reversed outcrop lies between the reversed and normal samples. It may not be in place, or it may be showing a real direction representing a polarity transition.

"These results suggest that many of the negative inclinations reported from the axial valleys of oceanic spreading centers may be explained by a complete, probably short, reversal during the uppermost Brunhes. Such a recent reversal may have significant implications for other studies which assume a constant cosmic ray flux in the upper atmosphere, such as carbon-14 dating." (R59)

Two statements of note are found in the preceding quotation: (1) That negative anomalies occur along the deep-sea spreading centers (about which we have no additional information); and (2) The possible evidence of a geomagnetic field in transition between one polarity and another (i.e., the shallowly reversed outcrop). See X3 for detailed transition scenarios.

Note that some of the excursions selected for special attention below also took place during the 10,000-50,000-year time span covered in this section.

Evidence for repeated rapid flip-flops of the geomagnetic field. Something unusual happened to the geomagnetic field just before the onset of the Brunhes polarity interval, as detailed below.

"The Earth's magnetic field may switch polarity, with magnetic north becoming south and vice versa, much faster than anyone thought. According to Stan Cisowski, of the University of California, Santa Barbara, the magnetic field changed direction three times about 700 000 years ago. Cisowski says that each reversal of polarity seems to have taken only a few hundred years rather than 2000 to 3000 years, as many geologists believe.

.....

"Cisowski's results come from a preliminary analysis of a core of sediment collected this spring near the Philippines as part of the Ocean Drilling Program. He estimates that sediment built up on the sea floor at a rate of 12 centimetres per 1000 years, about 10 times as fast as in most places. Because there is more sediment, it can be dated more precisely, with a resolution for the changes in polarity of a few hundred years. Cisowski says that the entire sequence of three reversals took about 2900 years, and each reversal may have taken only a few hundred years." (R51)

Referring to the same area of the Pacific and the same drilling program, an item in Science News mentions a 10,000-year-long reversal that transpired 1.1 million years ago. It is not certain how, if at all, this reversal is related to the triple excursion reported above. (R50) In any case, it is difficult to see how changes in the ponderous fluid core of the earth could change this rapidly, but then again, see X3 for more detailed scenarios. (WRC)

The Lake Mungo Paleomagnetic Excursion. High remanent magnetization is found at several places on earth and also on the moon. Geophysicists are hard put to explain how such localized areas can be created. R.S. Coe has detailed the well-known Lake Mungo, Australia, event.

"Indications of large and rapid excursions in the direction of the ancient geomagnetic field continue to create considerable excitement and debate in palaeomagnetic circles. Barbetti and McElhinny have published detailed evidence of a remarkable excursion at Lake Mungo, Australia, dated at about 30,000 yr ago, on which they had briefly reported previously. I consider here various simple sources, all in the Earth's outer core, that could account for that excursion---an eccentric radial dipole or current loop, an eccentric horizontal dipole, and a pair of eccentric radial current loops of opposite sign---and discuss the merits of each in light of the modern geomagnetic field and with regard to the magnitude and spatial extent of the anomalous field produced.

"Because most of the excursions proposed so far have been found in sediments and have not been convincingly documented over a sizable portion of the globe, several workers have suggested that some or most of them may reflect sedimentological rather than geomagnetic phenomena. The record of the Lake Mungo excursion, however, is contained in sedimentary material that was baked in prehistoric aboriginal fireplaces. Thus, sedimentological phenomena cannot be invoked to explain the anomalous directions because the natural remanent magnetisation is not detrital or diagenetic in origin but rather is thermoremanent. This type of magnetisation is not only the most reliable recorder of ancient field direction but is also the best suited for making estimates of ancient field intensity.

"The Lake Mungo excursion is especially intriguing because of the very high field intensity that Barbetti and McElhinny have found accompanying the large swing in field direction. The intensity estimates are as high as 1.83 Oe, about twice as strong as anywhere on the surface of the Earth today and three times what would be produced at that latitude by the maximum geomagnetic dipole moment previously reported for the past 8,500 yr. While the field was abnormally intense its direction was shallowly inclined first roughly west and then roughly east, very far from the normal field direction of an approximately axial and centered dipole.

.....

"At present, one can only conclude that if the very high field intensities are approximately correct and if the excursion was caused by non-dipole features similar in configuration to the modern ones, then unusually strong non-dipole fields must have occurred simultaneously over a significant portion of the rest of the world," (R16)

The above was written in 1977. Today, perhaps, one would be free to hypothesize localized magnetization due to asteroid/meteorite impact or some other catastrophic event. (WRC)

The Imuruk Lake excursion. R.J. Marino and B.B. Ellwood have introduced a cautionary note into the interpretation of paleomagnetic measurements.

"The discussions of late Quaternary magnetic stratigraphy have presented a complex variety of magnetic events and excursions, many with differing degrees of reliability. Several authors have warned against this reinforcement syndrome in interpreting unconfirmed palaeomagnetic events. In support of these admonitions, we report here that some apparent geomagnetic field excursions recorded in sediments may not represent short-term changes in the Earth's magnetic field."

NRM measurements from cores extracted from Imuruk Lake, Alaska, provide a continuous record of the geomagnetic field for a period of more than 10,000 years. A sharp change was recorded in magnetic inclination that correlated well timewise with the so-called Blake magnetic polarity event. Under ordinary circumstances, say Marino and Ellwood, one might assume that the Blake event had also been recorded at Imuruk Lake; but detailed analysis proved otherwise, as we continue with another quotation from their article.

"Normal sediments exhibit a characteristic primary magnetic fabric, whereas excursion sediments exhibit an anomalous distorted fabric. Several causes for the distorted magnetic fabric recorded in the excursion sediments, such as slumping, deposition by turbidity currents, secondary mineralisation, increases in biogenic activity, and other processes are possible. The main consideration, however, is that the excursion magnetic fabric is anomalous, and therefore the magnetic directions recorded in Core V are suspect. We suggest that without independent corroborative evidence, such excursions should be regarded with suspicion." (R17)

The Blake Event: 108,000-114,000 years ago.

"Abstract. The magnetic stratigraphy of seven cores of deep-sea sediment established the existence of a short interval of reversed polarity in the upper part of the Brunhes epoch of normal polarity. The reversed zone in the cores correlates well with paleontological boundaries and is named the Blake event. Its boundaries are estimated to be 108,000 and 114,000 years ago ± 10 percent." (R62)

Reversed magnetization in recent pyroclastics from Columbia. It is a basic tenet of paleomagnetism that the direction of NRM acquired by a sample is parallel to the ambient geomagnetic field. That this direction may actually be reversed is evident in pyroclastics from the 1985 eruption of Nevado del Ruiz, in Columbia. These pyroclastics demonstrated for the first time that self reversal can occur during the process of NRM aquisition. (R38) See quotation from this article in EZP1-X3.

Possible rapid field changes recorded by historical lava flows in Hawaii. J. Castro and L. Brown have reported some startling results from very recent Hawaiian lava flows.

"Two extensively sampled flows, the 1950 flow of Mauna Loa and the 1972 flow from Mauna Ulu, Kilauea, have been found to have paleomagnetic directions statistically different from the present geomagnetic field direction (PFD) in Hawaii. The 1950 flow shows very consistent, but shallow directions throughout the flow, with the mean inclination 6° shallower than the PFD. Directions from the 1972 flow vary from site to site both along the length of the unit and within vertical sections. Relative between-site consistency is low, with all sites but one having paleomagnetic directions distinct from the PFD, however the mean inclination for this flow, 33.4°, is only about 3° shallower than expected. The source of such anomalous behavior in the recording of ambient field directions is yet unknown, although several possible causes are examined." (R42) Brown is quoted in another article as saying that the geomagnetic field might have changed very quickly. (R46)

Episode of steep geomagnetic field inclination about 120,000 years ago. In studying the Riverbank Formation of northern California, K.L. Verosub found that for about 20,000 years the inclination of the geomagnetic field was significantly steeper than the geocentric axial dipole field at this site. Verosub argued that if the geomagnetic field can exhibit such steep episodes for tens of thousands of years, long episodes of shallow inclination are also likely. For example, the field inclination over the past 35,000 years has been markedly shallow. It is not unreasonable from these observations to predict that non-geocentric, axial components of the geomagnetic field may persist for as long as 50,000-100,000 years. Therefore, the time needed to average a geocentric axial dipole field may be several hundred thousand years. In paleomagnetic circles, it is assumed that only 10,000-25,000 years are required. If this assumption is incorrect, the consequences could be serious, as Verosub explains below.

"All paleomagnetic determinations of the apparent motion of plates and microplates depend upon the assumption that the paleomagnetic samples represent enough time for the field to have averaged to a geocentric axial dipole. If this time is significantly longer than has been assumed, or if it does not exist at all, then the results of some of these determinations will require reevaluation." (R22)

X2. Possible periodicity in the excursions of the geomagnetic field. Several scientists have thought they have detected periodicities in the intensity of the geomagnetic field when it is plotted against time. The major emphasis has centered upon the possible periodicity of reversals of the field; that is, the tendency of reversals to occur regularly, like the sunspot cycle, for example. If such a periodicity can be proved, the theorists must find either an intrinsic periodicity in the mechanism of the geodynamo (or any other model) or an external driving force that regularly forces the geodynamo to reverse its polarity. Of course, the external driving forces usually suggested involve astronomical phenomena, such as asteroid/meteorite impacts, even though no one actually knows how such impacts could be communicated to the geodynamo.

We begin the discussion with recent fluctuations (not reversals) of the geomagnetic field. Although these excursions are not as great as polarity reversals, the foregoing discussion still applies.

Possible periodicity of archeometrically measured fluctuations. Paleomagnetic measurements for the past 10,000 years are almost always archeometric, using fired clay artifacts. Some of the archeometric data introduced in X1 hinted at a periodicity in the fluctuations of the geomagnetic field in recent times. Unfortunately, the three estimates of periodicities in our files are quite different from one another.

In 1968, K. McDonald and R. Gunst asserted the following: "Data over the past ten thousand years, obtained from archaeological specimens, indicates...that the terrestrial dynamo undergoes more rapid fluctuations as well. These ups and downs seem to have a periodicity of about ten thousand years in fact." (R1)

The 1970 paper of S.P. Burlatskaya, mentioned in X1, states that the recent field fluctuations have periods between about 200 and 600 years. (R3)

Late in 1970, in the Journal of Geophysical Research, Dr. [K.] Kitazawa reports that the geomagnetic field reached its peak intensity 2,000 years ago, with a maximum value 1.6 times that at present. The minimum, only half the intensity of the present field, occurred about 5,500 years ago.

"It is still uncertain whether or not the change is truly periodic, the researcher says, but it does appear to conform to a regular curve." (R6) Based on the quoted numbers, the period would be 7,000 years. (WRC)

Early estimates of the periodicity of the geomagnetic field. Looking farther back into geological time, early investigators here, too, produced a wide range of estimates for reversal periodicity.

In 1969, C.G.A. Harrison wrote: "Known reversals of the Earth's magnetic field occur at a rate of five per million years. However, the methods whereby the reversal pattern has been established act as a high frequency cut-off filter and will not record two reversals as separate if they occur close to each other. It is thus probable that the true reversal rate is much greater than five per million years. By comparing the observed distribution of polarity interval lengths with a theoretical distribution it is shown that the most likely rate of reversal is close to ten per million years." (R2) Thus, as early as 1969, the problem of statistical methods employed in analyzing the reversal record came to the fore.

By 1982, the picture was not much clearer according to D.H. Tarling, who employed the word "randomly": "All geomagnetic models are constrained by the need to allow polarity reversals. It is generally agreed that reversals occurred randomly during over the past 48 million years but may have occurred more systematically before that." (R21)

A 15-million-year periodicity was claimed by A. Mazaud et al in 1983: "We have attempted to analyse the mathematical structure of the reversal frequency curve in detail and to determine whether the rhythmic fluctuation was indeed periodic. By modelling the time evolution of the reversal frequency, we find a dominant frequency corresponding to a period of ~ 15 Myr. This result represents one of the most persistent long-term periodicities ever reported for a geophysical phenomenon." (R23)

In the following year (1984), J.G. Negi and R.K. Tiwari, from the National Geophysical Research Institute, in Hyderabad, found statistical evidence for five different periodicities, as now detailed.

"The Indian team has analysed the geological record of magnetic reversals ---revealed by 'fossil magnetism' in the rocks---using a statistical tool called Walsh spectrum analysis. It shows statistically significant evidence of periodic geomagnetic reversals occurring at intervals of 285, 114, 64, 47 and 34 million years.

"The strongest of these 'signals', at 285 million years, is very close to the time it takes the Solar System to orbit once around the Galaxy---the 'galactic year'. The shorter periods also coincide with other astronomical rhythms." (R26) One sees now a strong urge to connect reversals to extraterrestrial phenomena. (WRC)

Claims for a 30-million-year periodicity. During the mid-1980s, considerable discussion ensued when some researchers pushed claims for a 30-million-year periodicity---all this in spite of the above assertion that a 285-million-year peridicity was the strongest! R.B. Stothers was a major proponent of the 30-million-year figure. We present next the Abstract from one of his papers, in which he states his position and, in addition, sketches the rather confused situation prevailing in 1986.

"Reversals of the Earth's magnetic field may occur with a certain regularity. Using observed percentages of normal and reversed polarity during different time intervals, Negi and Tiwari detected several significant periodicities, notably one of 32-34 Myr. Raup used the dates of individual reversals to propose a 30-Myr period in the frequency of reversals although Mazaud et al. obtained a periodicity of only 15 Myr. Like Negi and Tiwari's other detected short periods, the 15-Myr period may be harmonically related to a basic 30-Myr period. It has also been suggested that these are accidental periodicities arising in a short record, or are harmonics of the record itself. In fact, all of the cited studies have used different data, different record lengths and different methods of time-series analysis. Raup has consequently retracted his original claim. Here I present a much fuller analysis of the reversal record and show that a statistically significant period of ~ 30 Myr does formally exist, in spite of the cited differences." (R36)

Stothers' 30-million-year figure was thought by some to be only coincidental. The situation was reviewed anonymously in the New Scientist of August 25, 1988.

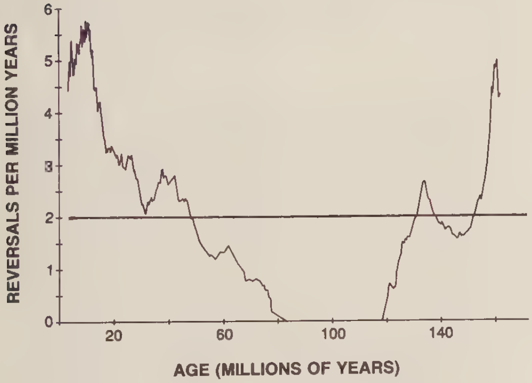
"Over the past five years, there have been claims and counter claims surrounding the precision of the periodicity in changes in magnetic fields and extinctions. Timothy Lutz, of the University of Pennsylvania, and Geoffrey Watson, of Princeton University, say that this periodicity is just coincidence. They say that, although there are peaks in the record of geomagnetic reversals, the overall pattern of peaks is explained by what they call a 'long-term variation model'.

"Their explanation for the appearance of a 30-million-year peak is that, for some unknown reason, the number of magnetic reversals occurring in each interval of five million years has been increasing over the past 80 million years. Statistical analyses that take no account of this trend are fooled into revealing a spurious 30 to 40 million year periodicity." (R48)

The varying rate of reversals. Toward the end of the 1980s, claims for a constant periodicity of field reversals over a long span of geological time had subsided considerably. In a lengthy review of paleomagnetism in Science, in 1990, R.T. Merrill and P.L. McFadden doubted that periodicity of any kind existed.

> "There have been several claims of a small-amplitude periodicity (period about 15 or 30 million years, depending on the method of analysis) superimposed on the mainly stochastic reversal record, but no robust statistical analysis has verified this. A particular problem with such verification is that minor revisions in the reversal chronology record can significantly affect apparent periodicities." (R54)

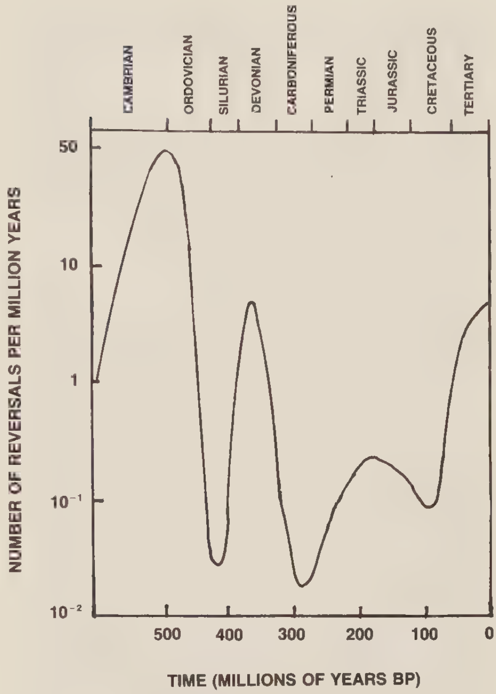
Instead of a fixed periodicity, Merrill and McFadden published a graph of estimated mean reversal rate extending back 165 million years. Inspection of this record reveals how sharply it differs from the horizontal line representing constant periodicity.



A graph of the rate of geomagnetic reversals as recorded in the rocks for the past 165 million years. (X2)

It is interesting to compare the curve of Merrill and McFadden with a similar graph presented by D. Mulholland in 1982, in which the geomagnetic reversal rate is projected back 600 million years. (R20) Although Merrill and McFadden had much better data, the curves are not too much different.

Conclusions. Just what, if anything, is anomalous about the rate of geomagnetic reversals? Actually, the variation in the rate of reversals simply exacerbates the major problems of paleomagnetism: explaining the origin of the of the



The rate at which geomagnetic reversals have occurred has fluctuated with time. (After J.A. Jacobs, X2)

geomagnetic field, its secular variation, and its apparent propensity to reverse itself. The periodicity of reversals---intrinsic or externally triggered---would be more difficult to explain than the vague trends seen in the accompanying illustrations. Any mechanism capable of generating the geomagnetic field is almost certain to exhibit several nonlinearities, and, therefore, be a good candidate for chaotic behavior. On the other hand, one can imagine a successful field-generating mechanism in which periodicity is an important intrinsic feature. In such a case, the geomagnetic field's apparent lack of strongly periodic behavior would be very anomalous. (WRC)

X3. Possible anomalous phenomena during reversals. When the geomagnetic field reverses, or even when it fluctuates wildly in an aborted reversal, new phenomena come to light which may help elucidate the reversal process itself as well as the origin of the "stable" geomagnetic field. First, we present a general description of what actually happens during a reversal, followed by a representative case history.

A generalized reversal scenario. "The usual picture of a reversal has been built up from many observations of remanent magnetism trapped in the earth's cooling magma and sedimentary rock. Most geophysicists today agree that it looks like this: Occasionally, for reasons yet unknown, the intensity of the geomagnetic dipole begins to diminish and, instead of recovering after a little dip, keeps on going toward zero. For about the first 3,000 years of this event, the dipole is still so much larger than the local field deviations that the decrease does not dramatically affect the location of the virtual magnetic pole.

"Eventually, however, the dipole effect is reduced so far that the local effects become more important; the field takes on a more complicated geometry, as if there were many dipoles, each dominant in its own place in the complex magnetic topography. Then after some 3,500 years of such erratic behavior, the earth's dipolelike field seems to regain its intensity, at the expense of the anomalies, reestablishing itself with an orientation nearly opposite the one with which it began. After about 10,000 years, the dipole is back to normal intensity, but its orientation has changed, a reversal is complete.

"The apparent pole path, thus, does not represent a true rotation of the dipole axis. It is merely evidence that the strength of the dipole is changing and that the local anomalies are, for the moment, stronger and dominant. From the evidence, it is impossible to tell how the dipole behaves during this period of local dominance, but most specialists believe that the decrease continues smoothly, with a change of sign as the sums of the fields cancel each other and the dipole effectively passes through zero." (R20)

The Steens Mountain reversal. Steens Mountain is in southeastern Oregon. There, in a 150-meter-thick section of layered basalt flows, is recorded an amazingly detailed magnetic picture of what happens to the intensity of the geomagnetic field and the position of the virtual geomagnetic pole (VGP) during a reversal. The Steen Mountain basalts are Miocene in age; 15.5 ± 0.3 million years old. (R43)

M. Prevot et al extracted 185 samples from different overlapping basalt flows at Steen Mountain. Of these, 157 provided useful magnetic data from 73 distinct flows. The researchers obtained 51 well-defined field vectors; 13 normal, 10 reversed, and 28 transitional. Quoting from their Abstract: "The record is complex, quite unlike that preicted by simple flooding or standing nondipole models. It begins with an estimated several thousand years of reversed polarity with an average intensity of 31.5 ± 8.5 μT, about one third lower than the expected Miocene intensity. This difference is interpreted as a long-term reduction of the dipole moment prior to the reversal.... Changes in the field vector are progressive but jerky, with at least two, and possibly three, large swings at astonishingly high rates. Each of those transitional geomagnetic impulses occurs when the field intensity is low (less than 10 μT) and is followed by an interval of directional stasis during which the magnitude of the field increases greatly." (R28)

What is anomalous about reversal scenarios? Of course, a reversal of the geomagnetic field in itself is really anomalous, even though the phenomenon itself is widely accepted (even embraced) by earth scientists. Reversals are anomalous because we do not understand exactly what sort of change occurs in the geodynamo and why it occurs at all. But, as pointed our earlier in this chapter, the geodynamo model possesses, in principle, the plasticity to accommodate reversals.

The reversal scenarios recorded at Steens Mountain and elsewhere around the planet, where multiple layers of volcanics are piled up, reveal three phenomena which seem anomalous: (1) the extreme rapidity of the changes in field intensity and direction; (2) the possibility of a quasistatic, intermediate state of the geomagnetic field during reversals; and (3) the apparent confinement of the paths of the virtual geomagnetic poles (VGPs) to a restricted band of longitudes during different reversals.

Extremely rapid field changes during reversals. The Steens Mountain record of a Miocene reversal (described above) produced evidence of rapid changes: "Geomagnetic impulses corresponding to astonishingly high rates of change of the field sometimes occur, suggesting that liquid velocity with the Earth's core increases during geomagnetic reversals." (R29; see also R61.) More specifically, the field changed as much as 3° per day, which implied that the liquid core was brushing the overlying mantle at a velocity of 1 kilometer/hour---far faster than anyone had supposed. (R52)

R.T. Merrill and P.L. McFadden commented on the implications of the Steens Mountain observations: "If the observations are to be believed as actual representations of the field behavior, then polarity transitions exhibit astonishing properties, including that the earth's magnetic field changed direction be a few tens of degrees in less than a year and underwent rapid changes in intensity. These changes are difficult to accept, because mantle shielding should smooth out such rapid changes and because the changes seem to require unrealistically high fluid velocities in the core." In effect, Merrill and McFadden questioned the interpretation of the data at Steens Mountain. (R54)

A possible third state for the geomagnetic field. In 1972, R.L. Wilson et al published a statistical survey of known examples of field reversals, which suggested that, in some cases, the field was quite strong at intermediate directions. Unfortunately, estimating the strengths of paleomagnetic fields is beset with experimental difficulties. However, J. Shaw, at Liverpool University, devised a new method for measuring intensities. "Applying the technique to 30 Icelandic lavas which have preserved one of the best known magnetic reversal transition zones, he finds clear evidence for a metastable state of the Earth's dipole in a direction at 90° to the Earth's axis. The rocks are about 1½ million years old.... If further observations prove it to be so, it is certain to modify theories of the Earth's dynamo." (R13) No further reference to this phenomenon has been found in the literature examined so far.

Confinement of VGP paths in longitude bands. "Using the VGP construction, it turns out that the paths are frequently confined with a narrow band of longitude. (If westward drift were an important part of the nondipole variation during a reversal, this would not happen.) We have not yet been clever enough to interpret this observation. There are also now several examples from North America, western Europe and the Soviet Union of sites at which different reversals have VGP paths confined to the same band of longitude. In one of the best-documented cases, three reversals with related paths took place over a period of about 1.4 million years and then there was an abrupt change." (R39)

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EZP3 Anomalies Implied by Determinations of Ancient Paleopoles

Description. Paleomagnetic measurements that indicate: (1) multiple paleopoles; (2) large divergence of magnetic and geographical poles; (3) large changes in the earth's radius over geological time; (4) polar wandering paths indicative of crustal slippage; and (5) polar wandering paths incompatible with continental drift.

Data Evaluation. Paleomagnetism has been the subject of intense research for several decades. For this reason, paleomagnetic data are abundant. Such data, however, are subject to assumptions about the origin of the geomagnetic field, its past behavior, and the reliability of natural remanent magnetization (NRM) as a measure of ancient geomagnetic fields. See EZP1 and EZP2. Rating: 2.

Anomaly Evaluation. This section impacts three widely held tenets of earth science:

1. The earth has remained approximately its present size during its history; that is, there was no significant expansion.
2. The crust and mantle do not slip about the core and thus change the angle between magnetic and geographical poles; i.e., "true polar wander" does not occur.

3, Continental drift has occurred, especially during the past 200 million years.

Since all three of these important beliefs are challenged to some degree by measurements of paleopoles, the anomaly rating here is high. Rating: 1.

Possible explanations. The earth has expanded considerably over the eons, making plate tectonics unnecessary.

Similar and Related Phenomena. All sections on paleomagnetism (EZP); objections to continental drift (ETL); evidence for earth expansion (ETL).

Examples

X1. Anomalous geomagnetic poles. The entries below are relatively old, as far as the discipline of paleomagnetism is concerned. It may be that they have somehow been accommodated or perhaps rejected.

Presence of two Tertiary poles. "Magnetizations observed in 95 specimens from more than 24 flows of Tertiary age in Israel indicate two directions of stable magnetization.....Most of the samples come from one structural block, which contain both typical Tertiary directions as well as anomalous directions, each of which involves a number of flows at widely separated stratigraphic positions and each of which contains both normal and reversed groups. The typical Tertiary pole is at 80°N, 114°W, whereas the anomalous pole is at 31°N, 47°W. This is very similar to other reported Tertiary and Cretaceous anomalous poles." (R3)

Anomalous pole positions from the Tertiary of California. Abstract. "Paleomagnetic data from some fine-grained intertidal muds of Pliocene age from Baja California yield pole positions which depart significantly from other Upper Tertiary pole positions for North America, whereas similar material of Recent age yields of pole position close to that of the present magnetic pole. The sense of displacement of the Pliocene pole position suggests that the collection site may have undergone a clockwise rotation of about 30° since the rocks were magnetized. If this is the case it suggests that portions of western North America have rotated as independent blocks in addition to the lateral translations typical of sea-floor spreading models." (R7) See ESR9 for discussion of "terranes."

Incompatibility of Permian paleomagnetic and paleontological data. Although paleomagnetic and paleontological data usually unite in support of plate tectonics, here is a case of divergence bearing the alarming title: "Could Paleomagnetism Be Wrong?"

"Continental movements are determined palaeomagnetically on the assumption that throughout the period covered by the rock record, the Earth's magnetic field has been axially dipolar. Needless to say, this is a reasonable assumption not internally inconsistent, but equally not susceptible to direct proof. Yet without such proof, palaeomagnetism falls to the ground. But Stehli (J. Geophys. Res. 75: 3325, 1970) now claims, on the basis of an analysis of palaeontological data, that for the Permian the axial hypothesis is not valid. Taken in isolation, his evidence is convincing because it is quantitative. His analysis is based on the observation that certain brachiopods are temperature dependent. The lower the temperature at any given place, the fewer brachiopod families there will be, which means that the diversity of brachiopod families will be a maximum around the equator but will fall off as the latitude increases. That this is the case is shown by the behaviour of Recent clams whose family diversity falls off quadratically with increasing latitude. The problem with Permian brachiopods from the northern hemisphere is that family diversity does not vary quadratically with palaeomagnetic latitude but does so when plotted on the present latitude grid. When plotted on the Permian palaeolatitude grid the Permian diversity bears no particular relationship to latitude, just as when the Recent clam diversity is plotted on the Permian palaeolatitude grid there is, as would be expected, no simple relationship. In short, the Permian axial field is not consistent with the Permian brachiopod diversity whereas the present latitude grid is. And if this is true for the Permian it could be true for other geological periods. That is why palaeomagnetics cannot afford to ignore Stehli's conclusions." (R4)

X2. Paleomagnetic measurements of ancient Earth radii. In actuality, there is no anomaly here is the sense that paleomagnetic measurements of ancient radii of our planet are in conflict with mainstream thinking. Most earth scientists believe that the earth's radius has changed little if any during geological time; and this is just what paleomagnetic measurements show. (R1, R2, R10) There is, however, a small band of scientists who, for numerous reasons, favor an expanding earth. (See ETL.) In their eyes, the paleomagnetically measured radii are anomalous. We recognize this dissension here by quoting the Summary from one determination of paleoradii and then giving the comments of S.W. Carey, a noted proponent of the expanding earth hypothesis.

"Summary. In recent years, a number of authors among whom Hilgenberg, Carey, Heezen, Egyed, Wilson, Dicke, Creer and Van Hilten must be mentioned, have suggested that the earth has expanded in the course of geological time. This hypothetical expansion can be tested by means of palaeomagnetism. Various methods are available: (1) the palaeomeridian method, (2) Ward's method of minimum dispersion and (3) the triangulation method.

.....

"All available computed earth radii are evaluated. Combined with new data, compiled by the present authors, they show that only small rates of earth expansion (including a zero rate of expansion, i.e., a constant earth radius) are compatible with the data

"It is pointed out that the Palaeomagnetic evidence for expansion can also be explained as a result of the presence of systematic errors in the palaeomagnetic inclination of the sediments, the occurrence of which is also known from other sources.

"Large expansion rates, such as those advocated by Hilgenberg and Carey must probably be rejected. This means that the reconstruction of ancient supercontinents which require these large rates of expansion are almost certainly invalid." (R2)

In his 1988 book Theories of the Earth and Universe, S.W. Carey replies to the various attempts at disproving earth expansion by paleomagnetic methods. He concentrated, in particular, on the so-called "minimum dispersion" or "minimum scattering" method.

"So in addition to the errors of the geometrical artifacts, the minimum-scatter method ignores the billions of minute adjustments or regional ruptures and on smaller and smaller scales right down to ordinary joints. If each joint yielded only one-thousandth of a degree, the error could be 10 degrees in a kilometer! As joints are inherently systematic, forming in response to the pervasive stress field, they are of necessity additive. The net result of this continuous adjustment of the continental slab to the changing radius is that the assumption of the present radius should always give the minimum scatter in the paleomagneticians' program.....by ignoring millions of tiny adjustments along millions of joints, paleomagneticians pretend to prove that the earth has not expanded." (R16)

X3. Paleopole overshoot. Closely related to the above-mentioned measurements of paleoradii are those of paleopoles. In this group of measurements, S.W. Carey sees support for the expanding earth hypothesis.

"In the early 1970's, paleomagneticians reported that if all the positions of the magnetic pole indicated by rocks magnetized during the last 2 million years throughout the world were combined statistically, they reproduced a rotation axis---a paleopole---within a small oval enclosing the present rotation pole. But the paleopole thus determined from any one region was a little beyond the mean paleopole determined from all regions. This is just what the expansion theory predicts, because angular distances on the earth's surface---which are what paleomagneticians measure---get progressively longer in kilometers as the radius increases." (R16)

X4. Paucity of Precambrian high-latitude poles. "Many apparent polar paths for the Precambrian have been published recently. A striking feature of these paths, besides their spaghetti-like appearance, is their bias for the equatorial zone, or their apparent aversion to high latitudes. Does this mean that contrary to the present pole, the ancient pole had a much greater affinity for the equatorial region? Perhaps high latitude poles do not exist, or they are not reported, or they are discriminated against in construction of polar paths. From data given here it seems that only the Pleistocene, the late Palaeozoic and Aphebian glacial deposits were truly formed in high latitudes. We discuss here whether some other mechanism is needed to explain the implied low latitude of deposition of other glacial deposits, and whether all these other deposits were genuinely polar but the palaeomagnetic record, as presently known, is deficient in high latitude poles." (R11)

X5. Excessive polar wander and slippage of the crust and mantle. Despite the occasional suggestion by popular writers on catastrophism (viz., J. White's Pole Shift, 1980) that the earth's crust and mantle has slipped relative to the liquid core, most scientists have scorned the thought. True, early paleomagnetic measurements did reveal that the poles had wandered a bit in the past, but this was explained at first as being due to sporadic geodynamo instabilities. But it soon became clear that the distances travelled by the paleopoles were too great for that interpretation. When continental drift became popular, "excess" polar wandering seemed to be accounted for by the wandering continents. Still further paleomagnetic research proved that polar wandering was still too great to be explained by any combination of continental drift plus geodynamo instability. (R13) The way was thus open for mainstream science to admit crustal slippage as a possibility. Besides, from the 1980s on, catastrophism was much more acceptable to earth scientists.

Actually, some scientists had advocated crustal slippage well before White's 1980 book. To illustrate, in 1973, R.B. Hargraves and R.A. Duncan embraced "true polar wandering".

"True polar wandering, sensu stricto, refers to a change in the position of the Earth as a whole or as outer lithosphere-mantle shell with respect to its rotation axis, which is presumed to be fixed in space. Such a change could conceivably result from redistributions of mass within the Earth (either by upward convection or downward subduction) whereby its moment of inertia axes shift. Should such a change occur, it would have palaeoclimatic impact and would represent a component of plate motion with respect to the geographic pole, which is common to all plates. Such true polar wandering has no a priori connexion with palaeomagnetism unless, as is conventionally assumed, well determined palaeomagnetic poles coincide with the geographic poles." (R9)

To check out their suspicion that the crust-and-mantle might have slipped over the hot core, Hargraves and Duncan compared paleomagnetic data and the traces left by thermal plumes rising through the crust, concluding: "Comparison of plume traces with palaeomagnetic data from lithospheric plates for the past 50 m.y. suggests that the mantle has rolled about its own independent axis within an outer lithospheric shell which as a whole is fixed in respect to the Earth's spin axis." (R9)

In the late 1980s, earth scientists began to publish papers that told of rapid, significant slippage between the crust-and-mantle and the liquid core. (R13) As above, such slippage is measured in terms of "true polar wandering". Just how much polar wandering is "true" can be difficult to determine; and its now-acknowledged existence certainly makes the reconstruction of ancient continents more difficult. To illustrate, R.A. Kerr wrote the following in 1987.

"But has polar wandering been rapid enough and has it persisted long enough to affect maps of continental positions? Recent estimates of the magnitude of past polar wandering have been dropping toward insignificance as better data have become available. But new analyses that extend the most thorough published study, which found only 5° of wander during the past 90 million years, show that a relatively sudden polar shift of 10° to 15° occurred between 70 million and 100 million years ago." Kerr points out that the cause of such a sudden shift is unknown, although it must have involved the redistribution of mass on or within the earth. Further, the magnitude of the glitch is comparable with continental drift. (R14)

In addition to the sudden slippage in the late Cretaceous (70-100 million years ago), V. Courtillot and J. Besse have reported a strange hiatus in true polar wandering, as related in the following quotation.

"True polar wander, the shifting of the entire mantle relative to the Earth's spin axis, has been reanalyzed. Over the last 200 million years, true polar wander has been fast (approximately 5 centimeters per year) most of the time, except for a remarkable standstill from 170 to 110 million years ago. This standstill correlates with a decrease in the reversal frequency of the geomagnetic field and episodes of continental breakup. Conversely, true polar wander is high when reversal frequency increases." (R15)

Courtillot and Besse propose that true polar wander is linked to the emission of hot thermals from the core-mantle boundary layer. They note further than two exceptional episodes of volcanism (at the Cretaceous-Tertiary and Permo-Triassic boundaries) may have been associated with thermals released after two long time spans when geomagnetic reversals were absent. The environmental catastrophes at these two boundaries are also correlated with mass extinctions. It has been fashionable to blame these extinctions on asteroid/comet impacts, but they may instead have been a consequence of "thermal and chemical couplings in the earth's multilayer heat engine". (R15)

In a roundabout way, therefore, paleomagnetic measurements of excess polar wandering challenge the popular hypothesis of astronomical catastrophism at several geological boundaries. Excess polar wandering is thus anomalous. It is also anomalous in the sense that crust-mantle slippage is not yet part of mainstream geological thinking. Finally, true polar wandering makes reconstruction of past maps of continent positions suspect, casting suspicion upon the sacrosanct hypothesis of plate tectonics.

X6. Paleomagnetic anomalies pertaining to continental drift. Continuing with the theme expressed at the end of X5, we review here some objections that have been raised against continental drift (plate tectonics) on paleomagnetic grounds.

A general objection to paleomagnetism and, therefore, continental drift. P.S. Wesson, a major critic of continental drift, asserts that the basic premise of paleomagnetism is violated: "Summing up the position as regards palaeomagnetism, we must concede that the coincidence of the Earth's rotational and magnetic axes in the past---the basis of the palaeomagnetic method---is untenable." Wesson uses as one of his arguments that the other planets besides the earth reveal large angular separations of their magnetic and spin axes, so that it is very unlikely that the earth's axes coincided in the past. (R5) Obviously, if paleomagnetism is basically flawed it cannot be employed to confirm continental drift.

Paleopole scattering and wandering. A.A. and H.A. Meyerhoff, also energetic critics of continental drift, maintain that paleomagnetism is inadequate to prove continental drift.

"Paleomagnetic methods apparently have little or no resolving power for studies of global tectonics. As the number of ancient pole determinations increases, the scatter of ancient pole positions has become so great, even from single localities and geologic provinces, that the circles of error for paleopoles from rocks of each age are wider than the Atlantic Ocean. From this fact it is apparent that paleomagnetic pole determinations cannot be used to show relative movements between continents." (R6)

The forgoing quotation is from a 1970 article. Paleomagnetic precision has improved a great deal since then, but the basic contention still seems valid.

The Meyerhoffs also remarked on the problem of polar wandering paths, as follows.

"Paleomagnetic studies of rocks of each age from each continent suggest a different polar wandering path, not only for each continent, but also for different parts of each continent. To make the different polar wandering curves coincide, paleomagneticists have attempted many schemes of continental drift. None has been successful." (R8) The reader should recognize that this is an extreme position from 1970. Even so, the interpretation of "true" polar wander in terms of crustal slippage (as in X5) simply worsens the situation. (WRC)

Common Precambrian polar wandering. Has continental drift been a factor in the evolution of the earth's surface throughout geological time? Most reconstructions of the earth's surface based on the results of plate tectonics are confined to the last 200 million years. It is reasonable to ask if continents also drifted in earlier times, especially the Precambrian. The observation that Precambrian polar wander paths from the continental cratons nearly coincide implies that the Precambrian continents were essentially fixed. B.J.J. Embleton and P.W. Schmidt state: "The results of the published palaeomagnetic analyses for North America, Africa and Australia strongly suggest that the cratons which comprise the individual continents retained their relationships for much of Precambrian time and that the younger, intervening mobile belts and major sutures did not result from convergence of previously widely separated microcontinents; their origin is ensialic. The implication is that tectonic styles have changed through geological time." (R12)

If continental drift is only a recent phenomenon, we must ask what event or condition, internal or external, initiated drifting. In other words, Precambrian polar wander curves imply some unrecognized event or change; they are, therefore, anomalous. (WRC)

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R12. Embleton, B.J.J., and Schmidt, P. W.; "Recognition of Common Precambrian Polar Wandering Reveals a Conflict with Plate Tectonics," Nature, 282:705, 1979. (X6) Dec. after p. 6
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EZP4 Inconsistencies in Paleomagnetic Measurements

Description. The inconsistencies of magnetostratigraphy in recording reversals of the geomagnetic field.

Background. Magnetostratigraphy assumes that the roughly 300 recognized polarity reversals are, for the most part, consistently detectable on a worldwide basis. It further assumes that the ages of these reversals, as measured in terrestrial deposits, can be assigned to the reversals detected in deepsea sediments, even though the two types of deposits are magnetized by different processes. (See EZP1.)

Data Evaluation. Discussions of the hazards of using magnetostratigraphic methods are rare in the scientific literature. Neither are missing and spurious reversals dealt with in detail in the literature examined so far. Rating: 3.

Anomaly Evaluation. Magnetostratigraphy has been important in establishing plate tectonics (and continental drift) as a valid scientific approach to the unraveling of the earth's history. Any inconsistencies would be highly anomalous. Rating: 1.

Possible Explanations. Optimistically, one can say that the inconsistencies are minor and merely imperfections in the geological record. On the other hand, pessimists can assert that magnetostratigraphy is a flawed method of correlating dates on a global scale.

Similar and Related Phenomena. Pitfalls in magnetostratigraphy (EZP1); the questioned reality of geomagnetic reversals (EZP1); the problems of radiometric dating (the foundation of magnetostratigraphy) (ESP1, ESP12).

Examples

X0. Background. The significance of magnetostratigraphy was well-stated by M.J. Oard in the following paragraph.

"The third main dating technique applied to Pleistocene deep-sea cores, as well as to other geological periods, is paleomagnetic stratigraphy, which is based on supposed reversals of the earth's magnetic field. Paleomagnetism has been primarily responsible for the revolution in the geological sciences caused by the plate tectonics theory. It was not until the magnetic stripe pattern was discovered on the ocean bottom and related to changes in geomagnetic polarity as the ocean crust spread from certain centers that earth scientists accepted continental drift and plate tectonics. Like other new geological methods, it contradicted other more-or-less established geological beliefs until a compromise was reached. This occurred in the field of paleomagnetism when it was discovered that certain index fossils used to date the Miocene-Pliocene boundary at nine million years ago were dated at five million years ago by the new method. Since paleomagnetism was considered more reliable, the Miocene-Pliocene boundary was changed to the new date, causing much previous literature to be updated. Paleomagnetism was also responsible for the revival and general acceptance of the old astronomical theory of the ice ages." (R4)

Although Oard called magnetostratigraphy a "dating technique" above, he later quoted G. Kukla and J.D.A. Zijderveld as follows.

"Magnetostratigraphy is not a dating technique. It only provides globally synchronous correlation planes, whose identification is possible by comparisons with other stratigraphic or radiometric data." (R3)

Magnetostratigraphy depends absolutely upon the standardized polarity scale on which field reversals are dated radiometrically or by fossil content. Wherever magnetic reversals are found, in land-based volcanics or in deep-sea sediments, they are matched with the polarity time scale. If the pattern in a deep-sea core can be matched, reversal for reversal, with a section of the polarity time scale, the dates of the scale are assumed to apply to the matched sample. It should be remarked that the polarity time scale was developed from terrestrial igneous rocks; magnetostratigraphy applies this scale to deep-sea sediments, which acquire their NRM in an entirely different way. Quite understandably, some scientists are wary of magnetostratigraphy.

G. Kukla and J.D.A. Zijderveld have expressed some doubts, referring first to the Gothenburg geomagnetic excursion discussed in EZP1.

"Controversy is growing over the existence of young excursions of the Earth's magnetic field such as the Gothenburg event. Are these features real? Are they true records of magnetic anomalies? Do they influence climate? Or are they merely a product of overlooked natural or artificial strata deformations? The recently reported detailed study of Koobi Fora formation in Kenya shows that the reversal stratigraphy of Pre-Brunhes formation is not without difficulties either. With all these problems, can paleomagnetic 'magic' still be taken seriously?" The authors go on in some detail concerning the kinds of errors that can creep into magnetostratigraphic analysis. (R3) Many of these we have already mentioned in EZP1.

As this section of the Catalog of Anomalies is being compiled (1990), the doubts expressed above seem to have been forgotten, for magnetostratigraphy is widely used in geology, and plate tectonics, which depends so heavily upon it, still reigns supreme.

X1. Lack of internal consistency of excursions in limited geographical areas. In view of the claim that magnetostratigraphy is everywhere valid, we look first in the small. The following paragraph was written by K.L. Verosub.

"The geomagnetic field is generated by a dynamo within the earth's core. If paleomagnetic excursions represent geomagnetic phenomena, they must arise from instability in the fluid motions of the core. In this case magnetic potential theory requires that paleomagnetic excursions have a coherent variation on a scale of at least several hundred to a thousand kilometers. We expect therefore that evidence for a paleomagnetic excursion should be internally consistent within sedimentary basins the size of lakes or small seas. Most anomalous paleomagnetic directions represent the results of a study of a single piston core from a given sedimentary basin. When multiple cores have been taken, the results have not always been internally consistent. For example, of 15 cores taken from the Gulf of Mexico, only eight appeared to record the excursion. More importantly, the magnetic signature, that is, the precise variation of declination and inclination, varied markedly from core to core." (R1)

X2. Many strong geomagnetic excursions are not detected globally. Even when internal consistency does prevail in the small, many excursions seem to be of limited geographical extent. M.J. Oard has pointed out that the famous Olduvai and Jaramillo events though well-established on land are rarely found in deep-sea cores. Oard goes on to list the anomalies of our present polarity epoch, the Brunhes normal epoch.

"Even the Brunhes normal epoch, which should be the most stable and easily measured since it is the most recent, is riddled with anomalies. Cox first suggested the theoretical possibility of short magnetic excursions in the Brunhes epoch. Since then, many have been found, causing much consternation and searching for non-geomagnetic mechanisms. The following Brunhes excursions have been suggested: (1) the Starno event about 3700 B.P.; (2) an excursion from the Great Lakes about 10,000 B.P.; (3) the Gothenburg excursion or 'flip' around 12,400 B.P.....(12) another possible event about 415,000 B.P. Some of these may be the same proposed event due to the dating problems. The Gothenburg 'flip' is an example of the many problems with paleomagnetic stratigraphy. The event has been found in many different sedimentary environments from Sweden, Canada, the North Atlantic, New Zealand, Czechoslovakia, the North Pacific, the Gulf of Mexico, Japan, and France. However, it is missing from just as many places all over the world, which indicates something is wrong somewhere. Some workers are skeptical of many of the claimed excursions." (R4)

X3. High-latitude heterochroneity. This ponderous term is applied to the apparent precocious appearance of some life forms in the polar regions. In one case, in which magnetostratigraphic dating was employed, L.J. Hickey et al claimed that late Cretaceous plant fossils found in the high Arctic predated their mid-latitude occurrence by as much as 18 million years. (R5) However, D.V. Kent et al criticized these results, calling the magnetic stratigraphy "suspect". In their reply, L.J. Hickey et al admitted that their magnetic evidence was "not as strong as we thought". (R6)

This example is presented to underscore the perils of magnetostratigraphic dating; it must be done with great care. See ESB10-X5 for further discussion. (WRC)

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EZP5 Correlations of Polarity Reversals with Other Phenomena

Description. Time-correlations of geomagnetic reversals with one or more of the following phenomena:

X1. Biological explosions
X2. Biological extinctions
X3. Tektite falls
X4. Climate changes
X5. Volcanism
X6. The earth's spin rate
X7. The earth's orbital eccentricity
X8. Impact events
X9. Black shale deposits
X10. Sealevel changes

This list does not exhaust the possibilities; we have noted only the most important and interesting correlates.

Data Evaluation. Humans are fascinated by time-correlations and have found many between geomagnetic reversals and other phenomena. While correlating reversals is not as popular as correlating sunspots, the literature here is voluminous. The real question, though, is how good the correlations are; that is, are they sufficiently significant statistically to imply cause-and-effect? Here, the number of claimed correlations is large. Many are multiple. Often the real forcing phenomenon is obscure. At this stage, it is difficult to say how good the correlations really are. Rating: 3.

Anomaly Evaluation. Actually, none of the correlations listed above is far-fetched in the scientific sense. Reasonable cause-and-effect chains can be drawn up for any one of them. In fact, they all might be involved. There is not much that is anomalous in the sense that physical laws are challenged. The problem is that we do not know which correlations represent cause-and-effect reality. Rating: 3.

Possible Explanations. None required.

Similar and Related Phenomena. Most of the phenomena listed in X1-X10 are covered elsewhere in the Catalog of Anomalies. See the cross references below. The reader might also find it worthwhile to peruse the subject indexes of the E- and G-series of Catalogs.

Examples

X1. Correlations of reversals with biological explosions. Many more papers try to link reversals of the geomagnetic field with biological extinctions than with biological explosions. Nevertheless, we have found a few older papers that connect reversals with higher terrestrial radiation levels and, in turn, with higher mutation rates and biological explosions or episodes of high speciation. This stance is in contrast to the usual claim that higher fluxes of radiation are harmful to life and are, instead, associated with biological extinctions. This apparent paradox can be explained by noting that the fossil record is frequently marked by biological extinctions that are followed by biological explosions. It may even be that magnetic reversals have nothing at all to do directly with extinction or explosions but are instead correlated with impacts of extraterrestrial objects that devastate the earth, leading to later rapid speciation. No one has any final answers here.

With this background in mind, we present excerpts from three papers that claim connections between magnetic reversals and biological explosions. The first is from 1966, by J.F. Simpson.

"Abstract. At certain times in the past, geomagnetic polarity reversals have caused fluctuations in the strength of the magnetospheric field. These in turn have modulated the cosmic ray flux impinging of the earth's surface and induced corresponding changes in sea level radiation environment. The magnitude of the increase in the overall background dose rate during geomagnetic field strength minima is a factor of 2 over the present dose rate. The maximum decrease during geomagnetic field strength maxima is undefined. The correlation in time between geomagnetic polarity reversals and evolutionary accelerations indicates that the increased intensity of ionizing radiation at those times may have enhanced the general mutation rate of organisms." (R1)

Just a year later, though, C.G.A. Harrison doubted that the increased radiation levels would induce biological significant biological speciation by itself. He proposed an intermediate phenomenon as the explanation of such correlations.

"During a reversal of the Earth's magnetic field, organisms at the equator will receive about 14 per cent more cosmic radiation than they do at present. Because of the comparatively high spontaneous mutation rate of organisms studied so far, it is extremely unlikely that this increase in radiation could have a significant effect on mutation rates. It is suggested that a possible cause of the correlation between microfaunal discontinuities and reversals should be looked for in a climatic change. Climatic changes could be brought about because of the control that the Earth's magnetic field may have on meteorological phenomena, or because of an increase of ionization at certain levels in the atmosphere." (R5)

In 1978, A. Wolfendale rather cautiously linked human evolution with reversals.

"When the Earth's field is in process of reversing---and we note that there have been 10 such reversals in the past 2.5 my---its intensity falls to a very low value and the solar protons can enter the Earth's atmosphere at any latitude. Big solar flares occurring during the few thousand years when the field is low pose a particular hazard. It is very interesting to note that recent Japanese work on field reversals from studies of deep-sea sediments shows that the field was virtually switched off for 10 000 to 20 000 years just over 1 my ago. The fact that evolution threw up man at about this time makes for an interesting coincidence." (R19)

X2. Correlations between geomagnetic reversals and biological extinctions. Almost as soon as geomagnetic reversals were discovered, scientists began claiming time correlations between the reversals and biological extinctions perceived in deep-sea cores. Actually, the correlations almost exclusively involved radiolaria and other "microfauna" in ocean-bottom sediments. It was also apparent that not all recognized extinctions were correlated with reversals---and vice versa. In addition, many reversals found correlated with extinctions were also correlated with climate changes, tektite falls, and other phenomena. Where more than two phenomena are synchronous, it is often difficult to identify cause-and-effect chains. Did a climate change cause the extinction or was it the absence of a protective magnetic field? Even today the causes of biological extinctions are being debated. Our purpose here is to record some of the important correlations and the debates that have surrounded them.

Typical correlations between reversals and bilogical extinctions.

1967. N.D. Watkins and H.G. Goodell established a correlation between reversals and extinctions of radiolaria in the Southern Ocean at 700,000 years ago. (R3) This is also the date assigned to the Australasian tektite fall.

1967. J.D. Hays and N.D. Opdyke: "Disappearances of some radiolaria correlate closely with magnetic reversals during the last 5 million years." (R4) This study was also made in Antarctic waters.

1970. J.P. Kennett and N.D. Watkins: "Studies of deep-sea sedimentary cores from Antarctic Pacific waters show that some volcanic maxima occurred when the geomagnetic polarity was changing. Upper mantle activity and geomagnetic polarity change may therefore be related. Coincidences of faunal extinction and geomagnetic polarity change may be explained by corresponding volcanically induced climatic changes." (R6)

1971. J.D. Hays: "A study of 28 deep-sea piston cores from high and low latitudes shows that during the last 2.5 m.y. eight species of Radiolaria became extinct. Prior to their extinction these species were widely distributed and became extinct isochronously throughout their geographic range. Six of the eight species disappeared in close proximity to magnetic reversals recorded in the sediment." (R10)

1980. R.E. Plotnick. Plotnick noted that many researchers had claimed a positive correlation between reversals and extinctions. In his Abstract, he described the results of his own study of this phenomenon: "Published associations between microfossil extinctions and magnetic reversals are reanalyzed using probabilistic techniques. The interrelationships of Phaneorzoic diversity and turnover rates to measurements of the magnetic field are examined through correlation analysis. Results indicate that no currently demonstrable relationship exists between faunal extinctions and geomagnetic reversals." (R23)

Despite Plotnick's negative conclusions, reports of reversal-extinction correlations are still being published. These later correlations also cross-correlate other phenomena. See X3-X10 for these multiple correlations.

1985. D.M. Raup suggested that the reversals of the geomagnetic field have a periodicity of about 30 million years, centered on 10, 40, 70,...million years ago. Biological extinctions are correlated with some of these reversals. (R34) See ESP2 for more on reversal periodicity.

Do geomagnetic field reversals cause extinctions directly? It was thought at first that the low intensity of the geomagnetic field during a reversal---a condition that might last for hundreds of years---would expose terrestrial life to lethal levels of cosmic radiation. This expectation proved to be false, as described below by I.K. Crain.

"Abstract. Although there are good correlations observed between magnetic reversals and biological extinctions, the radiation dosage hypothesis is insufficient to explain the agreement. In particular, the excess radiation was unlikely to have affected marine organisms. Experimental results indicate that very low magnetic fields have serious deleterious effects on a wide spectrum of organisms. It is proposed that the low magnetic field itself, rather than cosmic radiation has caused the mass extinctions." (R11)

Later, in 1978, A. Wolfendale remarked that such a conclusion might not hold if the field were very low during intense solar flares. (R19)

While the loss of the ambient magnetic field, of low intensity as it is, would not seem to be serious intuitively, experiments are not so sanguine.

"There are few published experimental reports on organisms living in magnetic fields below that of the earth, but, says Crain, the few conducted to date are consistent and show gross behavioral and biochemical abnormalities associated with life in a reduced magnetic field.

"After 72 hours, bacteria kept in a low magnetic field suffered a 15-fold reduction in reproduction. Locomotion of flatworms, protozoans and mollusks was found to be affected, and birds also showed significant changes in motor activity. Experiments on mice showed drastic changes in enzyme activity, and prolonged exposure produced a shortened life span, significant tissue changes and infertility. The effects of low magnetic fields, says Crain, are thus 'potentially lethal.'" (R9)

Desite these results, most scientists today focus on volcanism, climatic changes, and more physically impressive phenomena to wield the scythe of extinction.

X3. Correlations between geomagnetic reversals and tektite deposits. Ocean-drilling projects in several parts of the globe have retrieved cores containing tiny glassy globules called microtektites. In 1967, B. Glass and B.C. Heezen reported that in the Australasian region these globules are apparently correlated with the magnetic reversal that began the present Brunhes normal polarity epoch.

"The microscopic glassy objects which occur in sediments deposited in the Australasian area during and shortly after the last magnetic polarity event are apparently tektites. The last reversal occurred 0.7 x 10^6 yr ago; potassium-argon dates indicate that the Australasian tektites were formed 0.7 x 10^6 yr ago. The tektites were formed and deposited at the same time as the geomagnetic field reversed, and so both phenomena could have a common cause." (R2)

Several related matters arise here: (1) Some geologists claim that the Australasian tektites found on the land surface were deposited relatively recently despite their 700,000-year radiometric age (See ESM3.); (2) Tektites and microtektites are assumed to be the same although there are some differences; (3) The ages of microtektites, which are usually found only in deep-sea cores, are determined magnetostratigraphically; and (4) Field reversals more recent than 700,000 years have been claimed (See EZP2.) (WRC)

A more recent summary of the reversal-tektite correlation was presented by B. Schwarzschild.

"For the last 20 years, geologist Bill Glass and his colleagues at the University of Delaware have been documenting what appeared to be an extraordinary train of coincidences. Each of the three 'tektite events' associated with craters seems to have occurred at just about the time of a geomagnetic reversal. Examining dozens of sea floor cores from the vast Australasian strewnfield, for example, Glass and company found that the microtektite abundance as a function of stratum depth in each core always peaked unambiguously within 20 cm of the magnetic boundary marking the last reversal, 700 000 years ago. That is to say, the Australasian tektite event (for which there are several candidate craters on the Asian mainland) must have occurred within a few thousand years (either way) of the latest geomagnetic reversal. The third-most recent reversal---some 950 000 years ago---is similarly seen to be coincident with the Ivory Coast strewnfield, which is associated with the Bosumptwi crater in Ghana." Schwarzschild also mentions that the Ries crater in Germany is often associated the Czechoslovakian tektite strewnfield. (R40) The

Czechoslovakian tektites, though, are not microtektites; whereas the Ivory Coast strewnfield consists entirely of microtektites. Much more can be found on the subject of tektites and microtektites in ESM3. For example, there are two layers of microtektites associated with the North American strewnfield.

The correlation of the Ivory Coast microtektite fall with a geomagnetic field reversal, mentioned above, now seems to be rather shaky according to a recent study by D.A. Schneider and D.V. Kent. In their Abstract, they state:

> "The reported association of the Ivory Coast microtektite occurrence with the onset of the Jaramillo normal polarity subchron has given support to the notion that impact events can give rise to geomagnetic reversals. We evaluate the paleomagnetic stratigaphy of two critical deep-sea sediment cores bearing Ivory Coast microtektites and show that this event likely occurred during the Jaramillo subchron approximately 30 kY after its onset and 40 kY before its termination." (R50)

A causal relation between these particular microtektites and polarity change therefore seems unlikely.

X4. Correlations between geomagnetic reversals and climate changes. In EZF2-X3, the subject of correlations between excursions of the geomagnetic field and climate was broached. There, however, the discussion was limited to direct measurements of the field within historical times. The intention was the separation of phenomena associated with directly measured fields and the ancient fields determined by the methods of paleomagnetism. The reason for this caution lies in the doubts expressed about paleomagnetic methods in EZP1. There may be no need for this segregation, but it is part of our cataloging philosophy.

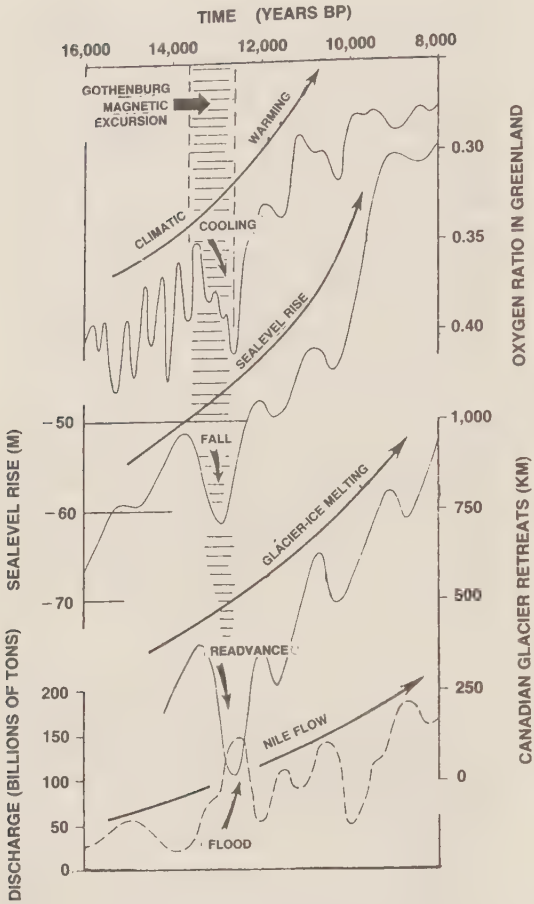
Here, in the context of paleomagnetism, G. Wollin has also been a leader in establishing field-climate correlations, as in the following item on "paleo" correlations.

The "paleo" correlations. Wollin discovered an impressive correlation between geomagnetism and climate in deepsea cores from many drilling sites, but especially from the Caribbean and the Pacific. These cores provided records of magnetic intensity, magnetic inclination, and temperature (as deduced from both oxygen-isotope ratios and foraminifera shells). As shown in the figure, stronger magnetic intensity can be linked to colder climates over the last 500,000 years. Explaining this correlation is difficult. One approach is to tie the intensity of the geomagnetic field to the Milankovitch 100,000-year eccentricity cycle, which in turn is linked to climate, ostensibly because of the varying sun-earth distance. (See ESR5.) The way in which magnetic intensity is tied to the Milankovitch eccentricity cycle is not as straightforward. Wollin suggested that, at high orbital eccentricities, the conducting fluid of the geodynamo is gravitationally distorted, resulting in a weaker magnetic intensity. (R10) This is so speculative that we must accord this correlation some degree of anomalousness! (WRC)

Note that Wollin worked with excursions of the geomagnetic field rather than with reversals per se. R.W. Fairbridge, too, tried to correlate climate with excursions, specifically with the Gothenburg excursion. (See EZP2-X1 for particulars on this pronounced, relatively recent excursion.)

In his studies of this 13,500 BP event, Fairbridge concluded that several dramatic climatic events occurred at the same time as the excursion: (1) a sudden re-advance of the great Laurentian ice sheet; (2) a fall in sea level; (3) a tremendous increase in the discharge of the Nile; and (4) a short reversal of the climatic warming trend that was underway at the time. In an offhand way, Fairbridge also remarked that the demise of Neanderthal man also seems to be correlated with the Gothenburg excursion! Fairbridge cautioned, however, that the Gothenburg-correlated climate changes were simply short-lived modifications of the Milankovitch cycle of climate changes caused by changes in the earth's orbit, (R13) This last point is interesting because in X7, we show correlations of excursions with the Milankovitch eccentricity cycle.

Other studies like that of Fairbridge can be found in the literature; and, of course, climate is often figured in multiple correlations of phenomena with excur-



Four climate indicators plotted for the period 8,000-16,000 BP. Sudden changes in these indicators occurred during the hypothesized Gothenburg geomagnetic excursion. (X4)

sions and reversals. We have room for only one more correlation which implies a causal relationship between the magnetic field and climate.

"A new statistical study by a researcher at the British Antarctic Survey, Cambridge, reinforces evidence already presented for a connection between reversals of the Earth's magnetic field and climatic changes. Christopher Doake reports that, for the period between 1.5 and 4.3 million years ago, climatic indicators show a 'significant correlation' with geomagnetic field reversals recorded for New Zealand. He looked at indicators, such as the changes in microfauna and oxygen isotopes within an ocean core taken from west of North Island, New Zealand." (R18)

How good are the reversal-climate correlations? After reviewing the published correlations, C.S.M. Doake, in 1978, found a rather strong correspondence.

Abstract. "Dates of climatic episodes in deep-sea cores are compared with the dates of palaeomagnetic polarity transitions during the Upper Pliocene period. The chance that the number of observed coincident dates will be a random occurrence can be as low as 3×10^{-4}, and if a simple probability model holds there is apparently a probability of about 0.4 that a climatic event will cause a magnetic field reversal." (R16)

As we shall see shortly, there are good rationales for Doake's supposing that climate changes caused the reversals and not vice versa as some authors imply.

Only four years after Doake's paper, D. Mulholland was totally negative about the validity of reversal-climate correlations.

"It was proposed seriously a few years ago that there was a correlation between magnetic reversals and major climatic changes. The implication was that this must be due to the breakdown of the magnetic shield that protects the earth from malign influences from interplanetary space. The folklore persists, but the assertions were actually based on spurious data. The observations that were used to support this idea showed no sign of the basic normal and reversed distribution of polarity. According to Chris Harrison, 'It was obvious that the samples were not recording the earth's magnetic field, but something else.' There is little evidence that the geodynamo affects the weather." (R25) Nevertheless, several reasonable mechanisms have been proposed; and, conversely, the climate may affect the geodynamo; or both may be affected simultaneously by some other phenomenon.

A 160-million-year survey of reversal rates and climate-change rates. The selected correlations presented above compared magnetic excursions and reversals event-for-event. Another way of establishing correlations is to compare the rates at which the events occur. This sort of analysis appears in a careful study by R. Muller and D. Morris, in which asteroid impacts are considered to be the forcing phenomenon, causing both reversals and climate changes. (See X8 for details about the mechanisms.) Although both reversals and climate changes are secondary effects. they are correlated---not event-for-event but in event rate versus time---although Muller and Morris believe that, with more detailed knowledge, event could be correlated with event. B. Schwarzschild elaborates below.

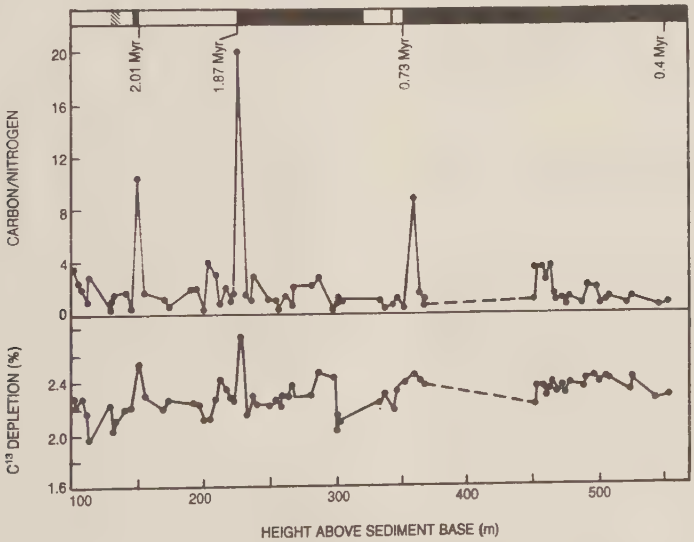
"In the calculations of Muller and Morris, a sea-level drop of 10 meters in a few centuries is sufficient to trigger a reversal. Do such abrupt drops happen often enough, and can we correlate them with the times of reversals? Some 300 geomagnetic reversals have been recorded for the last 170 million years, with a conspicuous dearth in the interval from 110 million to 75 million years before the present. For this same 170-million-year period, about 30 abrupt sea-level drops of 10-200 meters have been documented. This is thought to be only a small fraction of the steep drops that have actually occurred, and they have not yet been timed with sufficient precision to say how individual drops relate to individual reversals. But when one plots the rough time distribution of known sea-level drops, one finds the same dearth of occurrences in the period around 100 million years ago that characterizes the distribution of the reversals." (R40)

Some possible ways in which reversals might affect climate and vice versa. Since theories are only treated briefly in the Catalog of Anomalies, we merely list a few suggestions here.

The onset of a colder world climate might result in the buildup of so much ice that the earth's moment of inertia would be changed, and thus its period of rotation would also change. The change in spin rate might force the geodynamo into a different mode, causing a reversal. (R40)

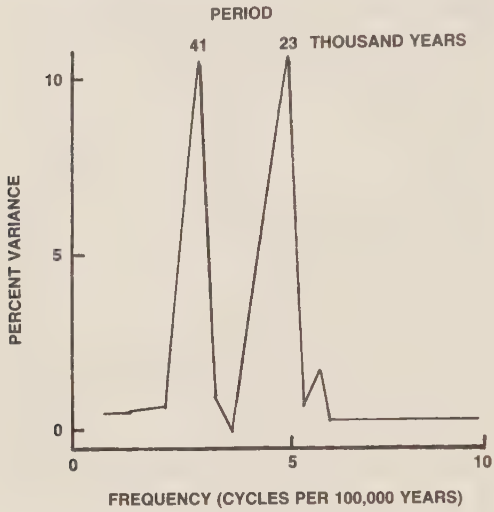
A reduced geomagnetic field would permit a greater flux of space radiation to impact the atmosphere and lower ionosphere, resulting in weather and climate changes. (R12, R18)

The ultimate forcing phenomenon, however, is probably neither the climate



(Top) The organic carbon/nitrogen ratio and (bottom) carbon-13 depletion curves correlate well for exposed lake sediments in Kashmir. The three sharp peaks coincide with geomagnetic reversals indicated above the graphs. (X4)

nor the reversals. For example, episodic changes in the earth's heat generation (as in a phase change) or core circulation could cause either or both climate changes and reversals. (R45) Also, external influences, such as asteroid/comet impacts could alter global climate and, in turn, the earth's spin rate and the state of the geomagnetic field. (R40) Obviously, there are several potential causal chains.



A power spectrum analysis of deep-sea sediments shows three cycles in global temperature with periods predicted by Milankovitch. (X4)

X5. Correlations between geomagnetic reversals and volcanism. The widespread eruption of volcanos and flood basalts signals an upsurge of activity within the earth, due perhaps to internal phase changes or instabilities. Since the geomagnetic field is held to be a core phenomenon, it is not surprising to find its behavior correlated with surface manifestations of internal thermal activity.

In 1970, J.P. Kennett and N.D. Watkins remarked that: "Studies of deep-sea sedimentary cores from Antarctic waters show that some volcanic maxima occurred when the geomagnetic polarity was changing. Upper mantle activity and geomagnetic polarity change may therefore be related." (R6)

Another interesting observation has been made by V.E. Courtillot, a proponent of a volcanic explanation of biological extinctions, rather than the more fashionable asteroid/comet impact hypothesis. Courtillot asserts that before both the Permian-Triassic and Cretaceous-Tertiary boundaries, where many extinctions occurred, there were long periods when the geomagnetic field did not reverse. In other words, the geomagnetic field, the earth's volcanos, and the biosphere were all stable together. (R39)

D.E. Loper et al, writing in 1988, also favored an internal cause of both reversals and volcanism. The following is from their Summary.

"We have reviewed the evidence for correlated periodic or episodic behavior of mass extinctions, volcanic activity, and frequency of reversals of the earth's magnetic field. While the evidence is not convincing, particularly that regarding volcanic activity, there is a strong indication that such correlations may be genuine. Assuming this to be the case, we have argued that the correlations are due to an internal, rather than an external cause, and have presented a model of unsteady flow in the D" layer of the earth to explain these correlations." (R45) In this model, the episodic driving force is found in core instability.

Despite the preceding readiness to accept a connection between volcanism and reversals of the geomagnetic field, there are demurrers, In 1990, W. Marzocchi and F. Mulargia published a study of volcanism in the Hawaiian Chain over the last 7.2 million years. They found: "no evidence supporting the existence of a correlation between eruptive activity and geomagnetic polarity and hence there is no evidence for a direct link between the core and surface phenomena." (R51)

X6. Correlations between geomagnetic reversals and changes in the earth's spin. We have already hinted (in X5) at a mechanism that could link field reversals and the earth's spin rate; namely, changes of the planet's moment of inertia, which lead to perturbations of the interior. (R16)

M.A. Whyte has also used changes in the earth's moment of inertia to tie together changes in many parameters. First, he described the possible subtle connections between the rate of the earth's rotation, the polarity of the magnetic field, the level of activity at the ocean ridges, the sea level, and the climate. He further noted that where these parameters show changes climatic instabilities probably led to mass extinctions. Whyte believes that these changes are likely stimulated by changes in the earth's interior. Astronomical catastrophism was not considered, perhaps because it was still out-of-style in 1977!

In his paper, Whyte first reviewed the use of shell-growth patterns to compute the rotational history of the earth. He noted next the close link between the earth's spin changes and changes in the geomagnetic field. This, he suggested, was due to changes in the moment of inertia. Whyte's final synthesis of all the multiple correlations is worth quoting.

"Though much work needs to be done to improve our knowledge of the factors considered here, the data present a coherent picture. The Cenozoic, the late Devonian to Permian and the Ordovician were times of deceleration of mantle spin velocity, of predominantly reversed polarity, of decreasing oceanic ridge activity, of global regression and of climatic deterioration leading to ice ages. By contrast, in the Silurian to early Upper Devonian and in the Mesozoic, there was acceleration of mantle spin velocity, predominance of normal polarity, increasing ocean ridge activity, global transgression and climatic amelioration. Turning points between phases of different type are marked by magnetic instability, possible climatic instability and by mass extinctions. Aborted turning points occurred in the middle Carboniferous and late Jurassic. Despite the many imperfections and biased nature of the geological record a subtle but distinctive background pattern can thus be detected in it. Whatever the cause may be, this pattern is not only a record of surface processes but also of deep seated events some of which may even have taken place within the Earth's core." (R14) Here again, both reversals and spin, though correlated, are driven, according to Whyte, by some internal episodic or periodic process. The anomaly is that we do not know what this process is.

X7. Correlations between geomagnetic reversals and the earth's orbital eccentricity. Anyone who has read X1-X6 can appreciate the difficulties scientists have in sorting out causes and effects in the multiple correlations presented in this section. In this entry, the earth's orbital eccentricity is the parameter under scrutiny. As the earth's distance from the sun changes, due to orbital eccentricity, the amount of solar radiation intercepted by the earth also varies; so does the gravitational force exerted by the sun. If there is a valid correlation between eccentricity and reversals, it probably stems from one or both of these physical factors; i.e., insolation or gravity.

When examining insolation as a causal factor, it should be recalled that the 100,000-year Milankovitch eccentricity cycle is thought to be prominent in many rhythmites. (ESR5) This 100,000-year signal apparently affects the global climate, sea level, ice inventory, and, as a result, the earth's moment of inertia and spin rate. The earth's spin, as mentioned earlier, could affect the geomagnetic field. This, then, is a possible link between eccentricity and reversals. But, as related below, a link involving gravity is not out of the question.

First, we present claims of correlations between eccentricity and reversals by G. Wollin et al and M.R. Rampino, in this order.

Abstract. "Our investigation of deep-sea climatic and magnetic records showing that high eccentricity of the earth's orbit, low magnetic field intensity and warm climate occur together indicates the relative importance of eccentricity as perhaps the phenomenon which has most consistently modulated both climate and magnetism for at least the past 2,000,000 years. A speculative hypothesis regarding the mechanism which may be responsible for a relationship between the eccentricity of the earth's orbit, geomagnetism, and climate is suggested." (R17)

"It is notable that the last four, and possibly five, times of maximum eccentricity of the Earth's orbit were apparently closely followed by magnetic excursions. Eccentricity maxima appear to coincide with brief periods (10^4 yr) of minimum ice cover (the interglacial periods) that follow rapid melting of Northern Hemisphere ice. Such rapid changes in water-mass distribution might lead to the subsequent magnetic excursions." (R22) Once again, this is the moment-of-inertia argument.

Linking changes of gravity with reversals. In the Abstract of Wollin et al above, a "speculative" hypothesis was promised. In a 1979 overview of these correlations, P.J. Smith also asked how eccentricity could be linked to reversals. He responded with Wollin's hypothesis.

"But why? For the time being that is anyone's guess; so Wollin and his colleagues have had a go at it themselves. They begin with the premise that because the density of the Earth's core is greater than that of the near-surface zone, the core-mantle boundary is less elliptical than the Earth's surface. They then argue that, as a result, the torque exerted by solar and lunar gravity on the core is smaller than that on the mantle; so the core tends to precess more slowly than the mantle. Moreover, as the Earth's orbit is eccentric, the solar gravitational field acting on the Earth has an annual variation that increases as the eccentricity increases. Therefore, when the eccentricity is greater, the difference between the torques acting on mantle and core is greater, and the tendency of the core and mantle to precess at different rates is enhanced." It is this change in precession rates that might affect the geomagnetic field. (R21) In general, earth scientists seem to favor the insolation link over this proposed gravitational link.

X8. Correlations between geomagnetic reversals and impact events. Since the early 1980s, the most popular "external influence" on geological and geophysical phenomena has been asteroid/comet impacts. That such impacts have indeed occurred can be determined best by the identification of the actual impacts structures (craters, astroblemes; see ETC4). Most earth scientists also accept that the presence of tektites and microtektites (ESM3) also imply impacts, even if no associated crater can be found. Another probable indicator of large impact events is the existence of iridium layers (ESC1-X1), such as the one at the Cretaceous-Tertiary boundary. At present, there are only a 100 or so fairly certain impact events registered, compared with some 300 recognized polarity reversals. Without doubt more events in both categories will be discovered as exploration progresses.

We could establish a cause-and-effect correlation if some major impact events could be definitely linked to reversals. Alternatively, if impact event periodicity matched polarity reversal periodicity, the correlators would have additional positive evidence. Even with convincing correlations at hand, most scientists would still want to see a physically realistic mechanism connecting impact events and reversals. It is time to take a brief look at these factors just listed.

Attempts to match major impact events with reversals. At first, the simultaneous occurrence of some impact events and reversals seemed easy enough to find. The Australasian microtektites, for example, clearly seemed to have fallen very close to the time of the last widely accepted reversal about 700,000 years ago. The same situation prevailed for the Ivory Coast microtektites, except that here a crater was also available. Then, as if to clinch the correlation, an important crater (the Ries Kessel crater in Germany) was found to have a pattern of magnetic polarities consistent with what one would expect if a reversal had occurred at the same time as the impact. (R20)

In 1990. however, doubts surfaced regarding all of these once-accepted correlations.

"[D.] Schneider and [D.] Kent have taken another look at sediments from off the Ivory Coast that contain microscopic, glassy debris from [the crater] Bosumtwi called microtektites. They located the reversal, as recorded by magnetic mineral grains, in a sediment layer below the layer containing the impact's microtektites. Their conclusion---the Bosumtwi debris fell to the sea floor 30,000 years after the reversal." Schneider and Kent have also asserted that the Ries Kessel evidence is "unconvincing" and, finally, that the Australasian microtektite time-correlation with the 700,000-year reversal is likely only "coincidental". (R46)

Attempts to match crater and reversal periodicities. Several different crater periodicities have been claimed, and debate still rages over whether there is really a periodic signal and, if there is, which period is correct. Unfortunately, crater ages are difficult to pin down with precision, and the statistics are very sensitive to changes in age estimates. (See ETC4 for details.)

The possible periodicity of polarity reversals was discussed in EZP2-X2. But, as with crater periodicity, many doubts have been raised, as in the following paragraph written by R.T. Merrill and P.L. McFadden.

"It is easy to 'see' slight periodicities in the magnetic reversal chronology data, when in fact none may exist. Thirty million year periodicities such as claimed most recently by Creer and Pal are found by using a fixed window length to analyze a finite reversal chronology record. Such a procedure will typically lead to erroneous periodicities. No correctly conditioned testing of the claimed periodicities has been published, and there is no reliable geomagnetic evidence per se showing that such a periodicity has been imposed upon the reversal process. In particular, it is important to note that the features in the reversal record that have been used to indicate slight periodicities are very susceptible to minor changes in the reversal chronology, such as the addition of one or two missed short reversal events. Thus although the question of periodicities remains open for the moment, it is safe to conclude that the observed polarity sequence can be predominantly, if not completely, described as originating from some nonstationary stochastic process." (R42)

Can large impacts really cause reversals? The two most frequently proposed mechanisms by which asteroid/comet impacts could initiate a polarity reversal are: (1) The "climate-change mechanism", in which the impact's dust clouds trigger a "cosmic winter" that changes the earth's distribution of ice and water, thence the planet's moment of inertia and spin rate, and ultimately the core circulation, precipitating a reversal. Much of this cause-and-effect chain is still speculative. (R37, R40, R42) (2) The "shock/ pressure mechanism". Here, a shock or pressure wave propagates through the crust and mantle to the core, where it induces changes in the flow of the core material (perhaps through a pressure effect on the freezing rate at the core-mantle interface). This disturbance may lead to a field reversal. (R28, R36, R42)

R.T. Merrill and P.L. McFadden have looked into both scenarios and have decided that the first is too uncertain and speculative, while the second effect is inadequate to produce reversals. They concluded: "External initiations for magnetic reversals can be ruled out on the basis of observational evidence as mechanisms for the vast majority of reversals, and probably for all reversals." (R42)

X9. Correlations between geomagnetic reversals and black shale deposits. This intriguing correlation is closely related to, perhaps inseparable from, the climate-reversal correlation (X4). E.R. Force details below his assessment of the geological record with this correlation in mind.

"The Mesozoic-Cenozoic histories of reversals in the earth's magnetic field and of periods of widespread anoxia in the ocean basins show a remarkable correlation: periods of black-shale deposition ('anoxic events') occur during lengthy periods without magnetic reversals ('quiet' periods). My assembly of published work indicates a remote connection between quiet periods and anoxic events and suggests its form. Magnetic quiet periods coincide with fast seafloor spreading. During these periods, buoyant spreading ridges displace seawater onto broad shelves, thus decreasing earth's albedo and causing global warming. Temperature gradients, from pole to equator decrease in surface waters, and the deep ocean currents of oxygenated polar waters wane. Oxygen minimum zones intensify and widen, anoxic conditions throughout entire basins are indicated by black shales deposited in the deep sea. These relations thus suggest that the earth's interior processes and its climate are related and their status recorded by both magnetic polarity and anoxic event chronologies of the earth." (R32)

X10. Correlations between geomagnetic reversals and sealevel changes. A connection between reversals and sealevel changes has been suggested in several of the preceding sections in association with the climate-change theory of reversals. The most popular interpretation of this correlation has been in terms of ocean water being converted into ice inventory. There is, however, another way in which this correlation could be consumated in cause-and-effect terms. S. Gaffin explained in the Abstract of his 1987 paper in Nature.

"In this letter I report a negative correlation and a phase difference of ~10 Myr between recent data on long-term eustatic sea-level change and geomagnetic reversal rate for the past 150 Myr. The phase difference is detectable both by visual inspection and through a correlation analysis. I also show that the same phase difference (but with a positive correlation) could theoretically have existed between this eustatic sea-level data and sea-floor creation rate. In light of the ridge-volume hypothesis of long-term eustasy, the analysis suggests that the sea-floor creation rate (and/or subduction rate) and geomagnetic reversal rate are closely associated and perhaps synchronized in their changes." (R41) In other words, both changes in sealevel and magnetic reversals have internal origins.

R.A. Muller and D.E. Morris responded to Gaffin's paper with a reiteration of the water-to-ice theory. (R43)

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