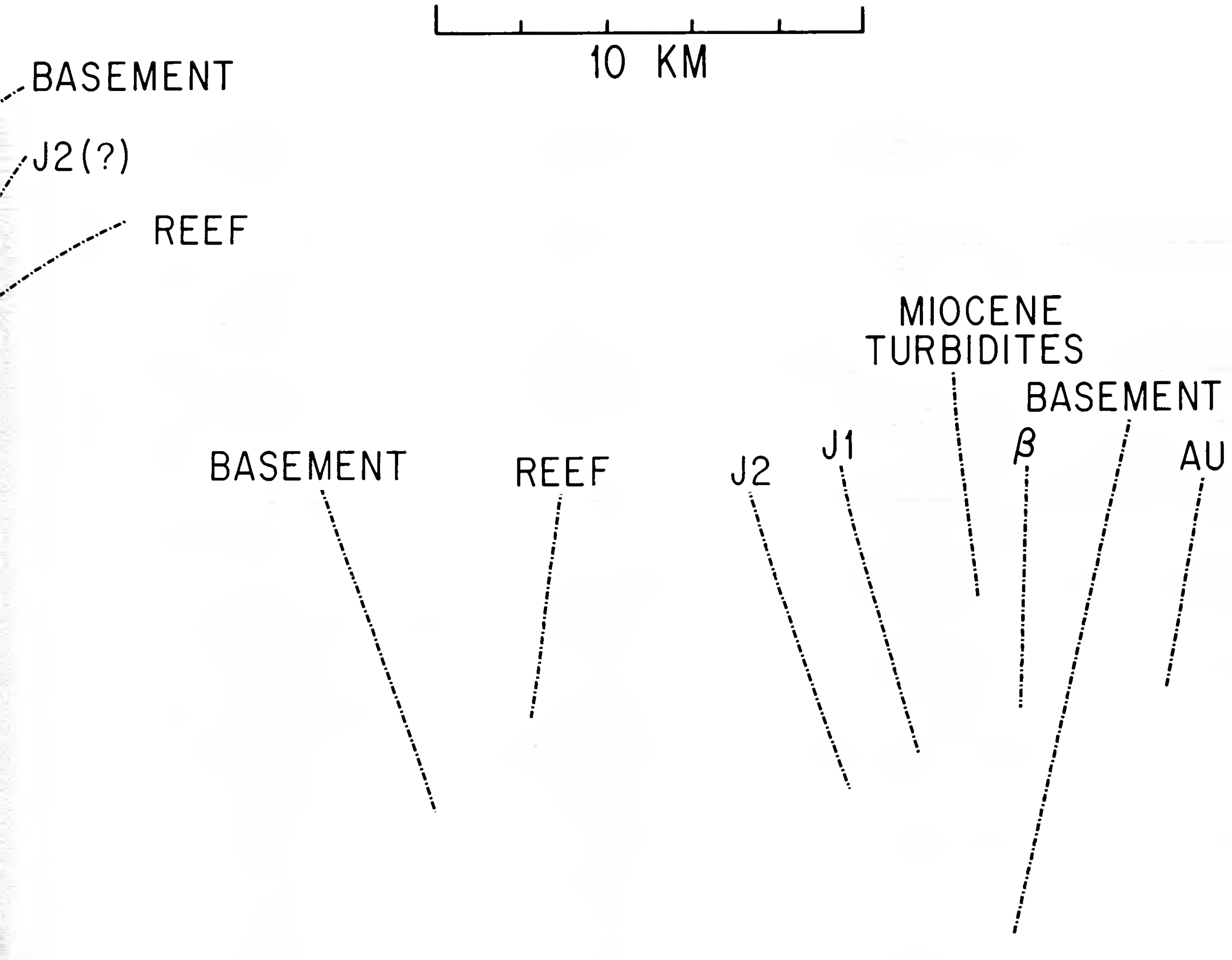

10 KM
BASEMENT
J2(?)
REEF
MIOCENE TURBIDITES
BASEMENT
BASEMENT
REEF
J2
J1
β
AU

# Oceanus®

## The International Magazine of Marine Science

Volume 22, Number 3, Fall 1979

William H. MacLeish, *Editor*
Paul R. Ryan, *Associate Editor*
Deborah Annan, *Editorial Assistant*

*Editorial Advisory Board*

Edward D. Goldberg, *Professor of Chemistry, Scripps Institution of Oceanography*
Charles D. Hollister, *Dean of Graduate Studies, Woods Hole Oceanographic Institution*
Holger W. Jannasch, *Senior Scientist, Department of Biology, Woods Hole Oceanographic Institution*
Judith T. Kildow, *Associate Professor of Ocean Policy, Department of Ocean Engineering, Massachusetts Institute of Technology*
John A. Knauss, *Dean of the Graduate School of Oceanography, University of Rhode Island*
Robert W. Morse, *Senior Scientist, Department of Ocean Engineering, and Director of the Marine Policy and Ocean Management Program, Woods Hole Oceanographic Institution*
Ned A. Ostenso, *Deputy Assistant Administrator for Research and Development, and Director, Office of Sea Grant, at the National Oceanic and Atmospheric Administration*
Allan R. Robinson, *Gordon McKay Professor of Geophysical Fluid Dynamics, Harvard University*
David A. Ross, *Associate Scientist, Department of Geology and Geophysics, Woods Hole Oceanographic Institution*
Derek W. Spencer, *Associate Director for Research, Woods Hole Oceanographic Institution*
Allyn C. Vine, *Senior Scientist Emeritus, Department of Geology and Geophysics, Woods Hole Oceanographic Institution*

*Published by Woods Hole Oceanographic Institution*

Charles F. Adams, *Chairman, Board of Trustees*
Paul M. Fye, *President of the Corporation*
Townsend Hornor, *President of the Associates*

John H. Steele, *Director of the Institution*

**Acknowledgment**
*The editors would like to acknowledge the advice and assistance given by Dr. James R. Heirtzler, Senior Scientist in the Department of Geology and Geophysics, Woods Hole Oceanographic Institution, in the development of this issue.*

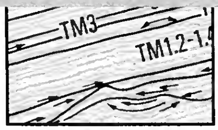
The views expressed in *Oceanus* are those of the authors and do not necessarily reflect those of Woods Hole Oceanographic Institution.

Editorial correspondence: *Oceanus*, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543. Telephone (617) 548-1400.

Subscription correspondence: All subscriptions, single copy orders, and change-of-address information should be addressed to *Oceanus* Subscription Department, 1172 Commonwealth Avenue, Boston, Mass. 02134. Urgent subscription matters should be referred to our editorial office, listed above. Please make checks payable to Woods Hole Oceanographic Institution. Subscription rates: one year, $10; two years, $18. Subscribers outside the U.S. or Canada please add $2 *per year* handling charge; checks accompanying foreign orders must be payable in U.S. currency and drawn on a U.S. bank. Current copy price, $2.75; forty percent discount on current copy orders of five or more. When sending change of address, please include mailing label. Claims for missing numbers will not be honored later than 3 months after publication; foreign claims, 5 months. For information on back issues, see page 80.

Postmaster: Please send Form 3579 to *Oceanus*, Woods Hole, Massachusetts 02543.

# Contents



*COVER: Part of a Common-Depth-Point seismic profile taken on the continental margin off Jacksonville, Florida, showing the outer Blake Spur and western Blake-Bahama basin. (Photograph courtesy USGS) BACK COVER: The formation and evolution of a passive continental margin.*

*Oceanus* (ISSN 0029-8182) is published quarterly by Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543. Second-class postage paid at Falmouth, Massachusetts, and additional mailing points.

# Oceanus®

The International Magazine of Marine Science

Volume 22, Number 3, Fall 1979

William H. MacLeish, *Editor*
Paul R. Ryan, *Associate Editor*
Deborah Annan, *Editorial Assistant*

*Editorial Advisory Board*

Edward D. Goldberg, *Professor of Chemistry, Scripps Institution of Oceano*
Charles D. Hollister, *Dean of Graduate Studies, Woods Hole Oceanographi*
Holger W. Jannasch, *Senior Scientist, Department of Biology, Woods Hole*
Judith T. Kildow, *Associate Professor of Ocean Policy, Department of Ocea*
*Massachusetts Institute of Technology*
John A. Knauss, *Dean of the Graduate School of Oceanography, University*
Robert W. Morse, *Senior Scientist, Department of Ocean Engineering, and*
*and Ocean Management Program, Woods Hole Oceanographic Institution*
Ned A. Ostenso, *Deputy Assistant Administrator for Research and Develop*
*at the National Oceanic and Atmospheric Administration*
Allan R. Robinson, *Gordon McKay Professor of Geophysical Fluid Dynamics*
David A. Ross, *Associate Scientist, Department of Geology and Geophysics*
Derek W. Spencer, *Associate Director for Research, Woods Hole Oceanogr*
Allyn C. Vine, *Senior Scientist Emeritus, Department of Geology and Geoph*

*Published by Woods Hole Oceanographic Institution*

Charles F. Adams, *Chairman, Board of Trustees*
Paul M. Fye, *President of the Corporation*
Townsend Hornor, *President of the Associates*

John H. Steele, *Director of the Institution*

The views expressed in *Oceanus* are those of the authors and do not necessarily reflect those of Woods Hole Oceanographic Institution.

Editorial correspondence: *Oceanus*, Woods Hole Oceanographic Institutic
Massachusetts 02543. Telephone (617) 548-1400.

Subscription correspondence: All subscriptions, single copy orders, and c
should be addressed to *Oceanus* Subscription Department, 1172 Common
02134. Urgent subscription matters should be referred to our editorial offic
checks payable to Woods Hole Oceanographic Institution. Subscription rat
$18. Subscribers outside the U.S. or Canada please add $2 *per year* handlin
foreign orders must be payable in U.S. currency and drawn on a U.S. bank.
percent discount on current copy orders of five or more. When sending change of address, please include mailing label. Claims for missing numbers will not be honored later than 3 months after publication; foreign claims, 5 months. For information on back issues, see page 80.

Postmaster: Please send Form 3579 to *Oceanus*, Woods Hole, Massachusetts 02543.

---

HAVE THE SUBSCRIPTION COUPONS BEEN DETACHED?

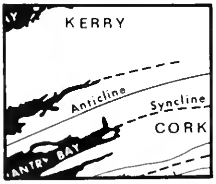
If someone else has made use of the coupons attached to this card, you can still subscribe. Just send a check — $10 for one year (four issues), $18 for two, $25 for three* — to this address:

Woods Hole
Oceanographic
Institution
Woods Hole, Mass.
02543

Please make check payable to Woods Hole Oceanographic Institution

*Outside U.S. and Canada, rates are $12 for one year, $22 for two, $31 for three. Checks for foreign orders must be payable in U.S. dollars and drawn on a U.S. bank.

# Contents



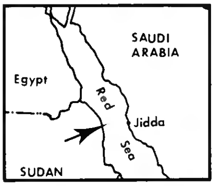
*THE EDGES OF THE OCEAN: AN INTRODUCTION*
*by Kevin Burke*
*The study of ocean/continent boundaries is central to the exploration for new oil and gas resources and provides data on the complex processes of plate tectonics.* **2**

*CONTINENTAL MARGINS: GEOLOGICAL AND GEOPHYSICAL RESEARCH NEEDS AND PROBLEMS*
*Extracts from a recent report sponsored by the Oceans Sciences Board of the National Research Council.* **10**

*ASSESSING OIL AND GAS RESOURCES ON THE U.S. CONTINENTAL MARGIN*
*by N. Terence Edgar and Kenneth C. Bayer*
*Assessments of oil and gas prospects on the U.S. continental margin have been taken with too much faith and too little understanding of how they are made and what they represent.* **12**

*OPHIOLITES: OCEAN CRUST ON LAND*
*by Suzanne O'Connell*
*Geologists are studying ophiolite rock assemblages on land for clues to the formation of ancient ocean crust, subduction processes, and continental growth.* **23**

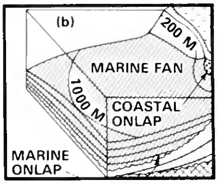
*THE RED SEA: A NEW OCEAN*
*by David A. Ross*
*The Red Sea is an example of a young ocean in the early stages of formation, and its hot brine areas have given rise to metal deposits thought to be worth billions of dollars.* **33**



*THE CONTINENTAL MARGINS OF THE WESTERN NORTH ATLANTIC*
*by John S. Schlee, David W. Folger, William P. Dillon, Kim D. Klitgord, and John A. Grow*
*In addition to allowing interpretation of earlier phases of the earth's history, study of the structural and sedimentary history of the U.S. Atlantic margin improves our chances for finding new hydrocarbon resources.* **40**

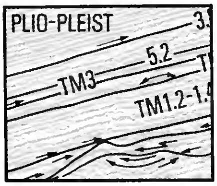
*THE EVOLUTION OF THE SOUTH ATLANTIC*
*by Floyd W. McCoy and Philip D. Rabinowitz*
*The South Atlantic is the most outstanding example of an ocean resulting from continental drift.* **48**

*SUBDUCTION ZONES: FACTS, IDEAS, AND SPECULATIONS*
*by Seiya Uyeda*
*The latest research indicates that there may be two different modes of subduction, triggering different kinds of tectonic activity.* **52**



*EARTHQUAKE HAZARDS*
*by Neville Donovan*
*Ninety percent of the world's seismic energy is released in areas around the Pacific basin, an area associated with many of the world's major deep-sea trenches.* **63**

*SEA-LEVEL CHANGES DURING THE TERTIARY*
*by Peter R. Vail and Jan Hardenbol*
*Study of global changes in sea level throughout geological history gives scientists knowledge of conditions that may have been conducive to the formation of petroleum.* **71**



*COVER: Part of a Common-Depth-Point seismic profile taken on the continental margin off Jacksonville, Florida, showing the outer Blake Spur and western Blake-Bahama basin. (Photograph courtesy USGS) BACK COVER: The formation and evolution of a passive continental margin.*

*Oceanus* (ISSN 0029-8182) is published quarterly by Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543. Second-class postage paid at Falmouth, Massachusetts, and additional mailing points.

*An example of the difference between Atlantic and Pacific-type margins. The eastern margin of South America is broad, with smooth expanses of sediment-covered sea floor; the western margin has a deep trench and few major sediment bodies. (From Physiographic diagram of the South Atlantic Ocean, Geological Society of America, copyright Bruce C. Heezen and Marie Tharp.)*

# The Edges of the Ocean:

## An Introduction

### by Kevin Burke

Although the enormous extent of the oceans became clear through voyages of discovery during the 15th and 16th centuries, realization that the ocean basins are underlain by structures that are quite different from those making up the continents came much later. The appreciation of the great depth of the oceans that came with the laying of transatlantic cables 100 years ago was essential to this understanding, and it is interesting to recall that the curve of depth distribution, published in 1921 and shown in Figure 1, was based on soundings obtained by the laborious wire method. Since then, millions of kilometers of continuous sonic depth determinations have confirmed the distribution that was established 60 years ago.

As Figure 1 shows, only about 10 percent of the earth's surface lies between sea level and oceanic depths. This area, although relatively small, is of great interest, not only because it marks a transition between the continents and the oceans, but also because the resources and environmental systems of the ocean margins are vital to the interests of all, especially to those millions of people living in populous areas along the continental coasts. The extent of petroleum exploration along continental margins and the lengthy discussions on margins at successive United Nations Law of the Sea conferences highlight this importance.

An early attempt to interpret the structure of the edge of the oceans was Eduard Suess' division in 1885 of coastal zones into Atlantic and Pacific types (Figure 2). The geological structure of Pacific-type coasts trends parallel to the coastline, while that of the Atlantic-type trends at a high angle. This simple division of coastlines does not work well everywhere, but, where it does, it is readily interpretable in terms of modern plate tectonics (see *Oceanus*, Vol. 17, No. 3). The long delay in understanding the nature of ocean margins is, in fact, no more than an aspect of the long delay in the recognition of the plate structure of the earth's surface.

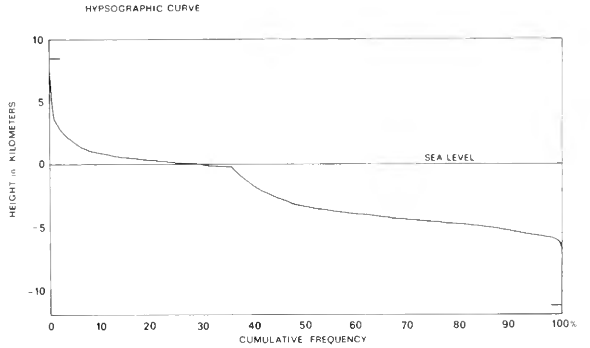


*Figure 1. Curve showing percentage of the earth's surface above any given elevation or depth. Most of the earth's surface lies near sea level or at oceanic depths. Only about 10 percent lies between sea level and oceanic depths and forms the edges of the oceans. (From J.F. Dewey, after Kossinna, 1921)*

The various theories of continental drift represent the best early attempts at understanding ocean margins. The excellent fit of the continents around the Atlantic (Figure 3) — the earliest strong evidence for continental drift — implies the breaking up of a larger supercontinent, Pangaea. The Atlantic grew, said Alfred Wegener in the early 1900s, where this break happened. This conception leads to a simple interpretation of the geological structure of ocean margins as separating ruptured continental material from relatively younger ocean floor rocks, a thick wedge of sediments accumulating across the continental margin as the ocean grows. The model is readily applicable to the margins of the Atlantic Ocean, but does not work so well in the Pacific and some other parts of the world. Proponents of hypotheses of continental drift embodying substantial expansion of the earth were ready to apply this simple model to all continental margins, and it was this readiness that gave an impetus to the imaginative syntheses of S. Warren Carey 25 years ago. For a variety of reasons, most earth scientists found and still find the idea of substantial expansion of the earth hard to accept (for one thing, the amount of work required against gravity is mind-boggling).

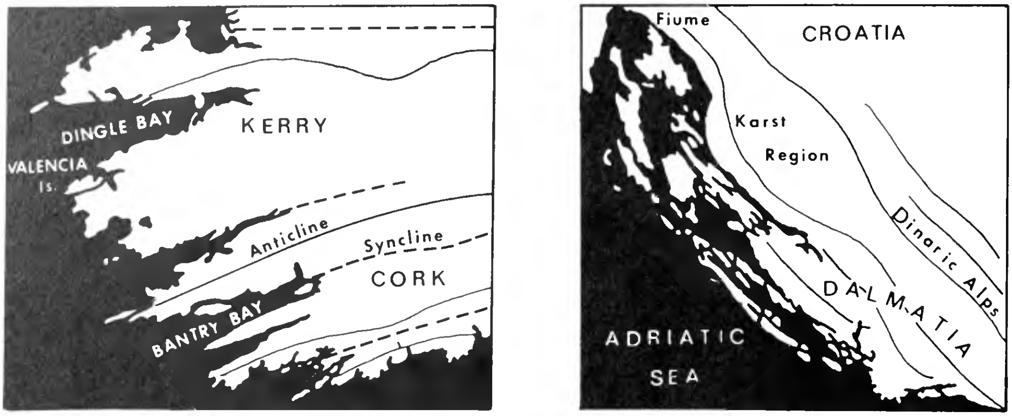


*Figure 2. Suess, 100 years ago, classified coasts as of Atlantic-type, left, in which geologic structure trends at a high angle to the coast, and Pacific-type, right, where structure trends parallel to the coast. (Reprinted with permission of Thomas Nelson and Sons, Ltd., from Holmes,* Principles of Physical Geology, *2nd Edition, © 1965)*

A more significant advance came with J. Tuzo Wilson's recognition of the plate structure of the lithosphere in 1965. Awareness that the lithosphere was broken into rigid plates, moving with respect to each other along tectonically active boundaries of three kinds, led directly to a clearer understanding of the nature of continental margins. The validity of the continental drifter's interpretation of Atlantic margins was established. These margins formed at divergent plate boundaries and, as the ocean grew and the divergent boundary continued to spread, the two continental fragments were carried symmetrically away from each other. At the same time, their edges were draped in young sediments. The contrasting character of Pacific coasts became understandable once it was recognized that they are places where the lithosphere is returning to the mantle and that most Pacific margins mark boundaries across which plates converge. Coasts associated with the third kind of margin, the transform margin at which plates slide past each other, are known but are less common than the other two. Thus plate tectonics permits a simple general classification of ocean margins, and the articles in this issue of *Oceanus* deal mainly with margins within this framework.

### Atlantic-Type Margins

More articles in this issue deal with Atlantic-type margins than with other aspects of ocean/continent boundaries. There are a number of reasons for this, but perhaps the most important is that sediment accumulation on Atlantic-type margins greatly exceeds that on Pacific-type. Many of the world's great sediment-carrying rivers flow into the Atlantic and its fringing seas (the Amazon, the Rhine, the Mississippi, the Congo, and the Niger rivers are examples), and wedges of sediment formed on the borders of the Atlantic include major oil- and gas-producing areas. This concentration has helped to foster research.

During the decade since earth scientists became generally aware of the plate structure of the lithosphere, Atlantic-type margin studies have evolved from interpretations based on the simple continental rupture model inherited from continental drift to more elaborate models, including allowance for factors that modify the development of the continental margin. The most generally recognized of these factors is the subsidence of margins as they cool with age. Young oceans, such as the Red Sea (see page 33), have high ground along their margins. Examples are the hills of Egypt and Sudan that border the Red Sea. Observations on more mature margins, such as the eastern United States, show a subsidence of about 3 kilometers over 150 million years. The rate of subsidence declines with time and, for this reason, can be realistically attributed to the cooling of the margin as it moves across the earth's surface away from the hot, young plate boundary of the mid-oceanic ridge.

One effect of this thermal subsidence is to increase the volume of sediment that accumulates at the continental margin by erosion from the continent. The accumulation of sediments becomes even thicker because the lithosphere underlying a sediment pile responds to the imposition of the sediment load by downward flexure. The lithosphere can be thought of as an elastic layer overlying a fluid asthenosphere. When the lithosphere is loaded, its downward flexure is accommodated by lateral movement of material in the underlying asthenosphere. John Schlee and his colleagues (see page 40) show that the sediment wedge along the Atlantic coast of the United States has reached a maximum thickness of about 15 kilometers in the 160 million years since West Africa and North America separated.

The kind of sediments forming the thick wedge at an Atlantic margin changes as the ocean grows. Comparison between the oceans of different ages described in this issue — the Red Sea, not more than 25 million years old, the South Atlantic, about 130 million years old, and the Central Atlantic, about 160 million years old — shows that all marginal wedges started with sediments, such as those accumulating in the East African Rift today, and that deposition of these generally coarse, rapidly accumulated sediments was commonly followed by limestone formation. This is the stage the Red Sea has reached, and it is apparent there that limestone deposition owes something to the proximity of hills close to the coast preventing clastic sediments from reaching the shore. Widespread limestone accumulation in the Central and South Atlantic continued for about 20 million years, and was generally followed by the accumulation of marine sands and muds. This has persisted since, but, as the ocean matures, sediment distribution along the margin becomes less uniform until nearly all the sediment being brought into the mature Atlantic Ocean today comes from about 10 large rivers.

The outstanding scientific result of the intense exploration of continental margins for petroleum has been to throw a new light on the way in which the continental margin sediment wedge develops. Peter Vail in this issue (see page 71) reports on the results of work at the Exxon Production Research Laboratory in Houston, Texas. Study of enormous amounts of seismic reflection data and complementary exploration well records has revealed a worldwide pattern of unconformities (gaps in sedimentation), resulting from global changes in sea level. Sea level has oscillated throughout geologic time and Vail and his colleagues, following the pioneer work of L.L. Sloss, have shown that a detailed record of these oscillations is preserved as unconformities in sediment piles. The oscillation of sea level results from a number of causes, including such relatively unusual processes as the removal of significant amounts of water from the ocean to make ice caps and its return when the ice caps melt, but the main cause seems to be fluctuations in the rate at which ocean floor is made.

Young ocean floor is hot and, because it is hot, it occupies a large volume. As ocean floor ages, it cools, and occupies a smaller volume. At the end of the Cretaceous Period (from 136 million to 65 million years ago), sea level was very high, and large parts of the continents were flooded. This appears to have been the result of an unusually high rate of ocean floor production (almost twice as great as at present) in the Late Cretaceous. The average age of the ocean floor was abnormally young and so its volume was large, forcing water out of the ocean basins up onto the continents.

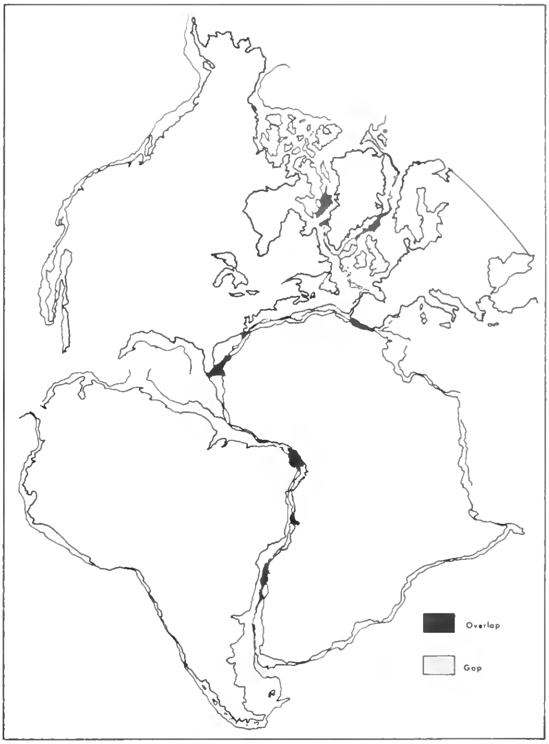


*Figure 3. The fit of the continents around the Atlantic. The excellence of this fit, recognized by early students of continental drift, led to the first realistic interpretation of the geologic structure of continental margins as separating ruptured old continental material from younger ocean floor with a completely different structure. (Adapted from Bullard, and others, Philosophical Transactions of the Royal Society, London, 1965)*

Walter Pitman of the Lamont-Doherty Geological Observatory at Columbia University has shown that there is a subtle interplay between the oscillations of sea level and the subsidence of Atlantic-type continental margins. The rate of thermal subsidence declines with age on an Atlantic-type margin, but the sense of movement is always downward. The rate of subsidence through loading depends on the rate of sediment supply, but its sense of movement also is always downward. Sea-level oscillations can generate both relative upward movement of the margin (as sea level falls) and downward movement (as sea level rises). If the sequence and timing of sea level changes are known (from the work of Vail and his colleagues), the rate of thermal subsidence (from the age of the margin) and the rate of sediment supply also are known. It thus should be possible to describe the development of an Atlantic-type margin over any

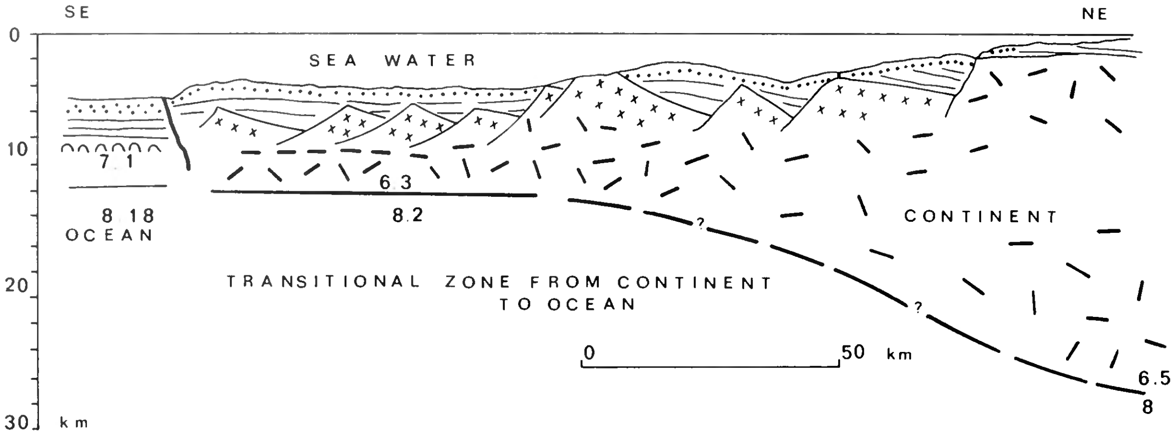


*Figure 4. Transitional zone between continent and ocean, with Brittany on the right and the Bay of Bascay on the left. Dashed lines represent continental crust and semi-circles oceanic crust. Crosses are rift-filling sediments and overlying lines are Cretaceous sediments deposited after formation of the ocean began. Dots represent Cenozoic sediments that are unusually thin, permitting the structure to be particularly well seen. Numbers illustrate the sharp change in seismic P (primary) wave velocity (in kilometers per second) observed at the base of the crust. The continental crust was hot during rifting and stretched enormously as a response to tension. As a result, it is abnormally thin over 150 kilometers. Overlying rift-filling sediments were colder and accommodated the extension by breaking along the curved faults. (Adapted from Charpal, and others,* Nature, *1978)*

time interval, comparing it with observation. Both transgressions of the sea onto the continent and regressions should be predictable. Pitman has done this for the New York Bight area with striking success.

The last decade has shown great advances in Atlantic margin studies, but there are many outstanding questions that have hardly begun to be answered. For example, geophysical modelling of the structure of the edge of the oceans has been based on the simple concept, inherited from continental drift, of a sharp break at the ocean margin. This is implicit in the good fit of the oceans around a closed Atlantic, and it works well on a global scale (say, on a 1,000-kilometer scale), but it is becoming increasingly clear that on a smaller scale, it is too simplified and that the boundary between oceans and continents is transitional typically over distances of about 100 kilometers. Evidence of the transitional character of Atlantic-type margins comes from places where the margin has either escaped deep burial under sediments, or has been exhumed following burial.

Figure 4 shows the kind of transitional margin that is being found in these areas. The continental crust, elevated in temperature at the time of rupture to a level at which it flows rather than breaks, appears to have stretched and thinned, while overlying sediments have adjusted to this flow by breaking along huge curved normal faults that extend the area occupied by the sediment pile to more than twice that occupied at the time of deposition.

David Ross in his article on the Red Sea (see page 33) points out the difficulties that are involved in using a model involving a sharp break at the continental margin, and John Schlee and Floyd McCoy use the abrupt continental margin model in their treatments of the Central and South Atlantic only because the zone of transition is so deeply buried under sediment that it is impossible to discriminate between an abrupt and a transitional model, although geophysical evidence from the South Atlantic suggests such a zone of transition.

An approach to Atlantic margins that I have found particularly useful is to see how the development of a particular margin varies along its length, and to seek explanations for this variation. For example: huge volumes of salt and anhydrite* occur among the early formed sediments on both sides of the South Atlantic north of the Walvis Ridge, on both sides of the Gulf of Mexico, and off Morocco and Nova Scotia (Figure 5). These evaporites were formed by the evaporation of sea water, and their absence from neighboring parts of the Atlantic margin is primarily the result of climatic differences. Adjoining areas lack the evaporites because they were, at the critical time, in latitudes where evaporation did not exceed precipitation. Other significant factors were: proximity to the waters of a large ocean, and the existence of structural barriers to the flow of water. This kind of analysis indicates that, although the basic processes governing the development of Atlantic-type margins are well understood, the way in which they interact in a particular case may be complex, and that the development of individual margins has to be analyzed in detail. The strength of our position,

---

*A mineral, anhydrous calcium sulfate, $CaSO_4$ — commonly found in large quantities in evaporite beds.

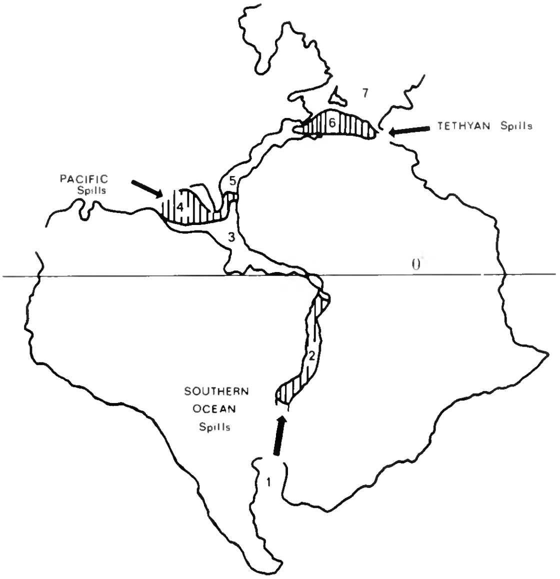


*Figure 5. Huge salt deposits (lined areas) were formed as the Atlantic began to open, and are now found at its margins. These deposits are confined to zones 2, 4, and 6. In zones 1, 3, and 7, there was an excess of precipitation over evaporation; thus salts could not form. In zone 5, salts are of restricted occurrence, apparently because access of salt water from the Pacific and Tethyan (former Mediterranean) oceans was structurally restricted. Line is a Mesozoic equator. (Drawn by J.F. Dewey, Geology, 1975)*

compared with 15 years ago, is that we now have a much better understanding of how the mechanical processes operate, and can apply them to interpreting specific histories.

A consideration that seems to be of dominant importance in analyzing Atlantic margins is that many features are determined by structural developments during the stage of rifting that precedes ocean formation — analogous to conditions in the East African Rift today. Figure 6a depicts a rift pattern similar to that in East Africa, which is developing into a typical Atlantic-type ocean with headlands and embayments. The map pattern of the mature ocean margin is thus determined before any ocean forms. A feature of this model is that it predicts the occurrence of numerous "failed" rifts in the two continental fragments (Figure 6b shows, on a closed Atlantic, the distribution of some failed rifts).

Finally, it has to be borne in mind that the development of the margin of an ocean in one area can be influenced by events a long way away (Figure 7). Late in its history, during the latter half of the Cenozoic Era (since 40 million years ago), part of the Atlantic margin of the United States suffered erosion by a deep, southward flowing current. Material eroded from the margin has been

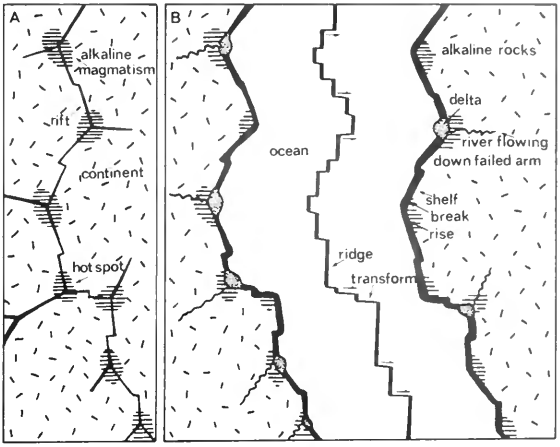


*Figure 6a. An idealized rift system within a continent (A), left (based on the East African system), is shown as controlling the shape of the coastline of an Atlantic-type ocean (B), right, that later developed from the rift. Failed rifts strike into the continent from the shores of the mature ocean. (Drawn by J.F. Dewey, Geology, 1974).*

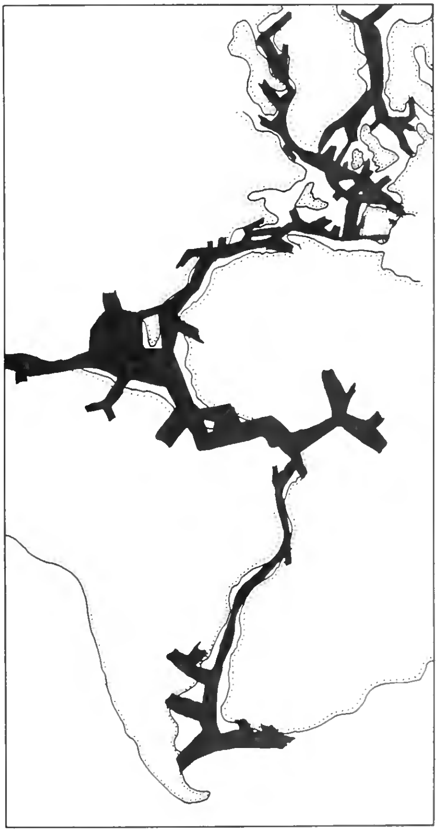


*Figure 6b. By comparison with the idealized pattern, shown in Figure 6a, the pattern of rifts striking into the continents around the Atlantic Ocean is very complex as shown on this version of a closed Atlantic. (©Copyright OTC, 1977)*

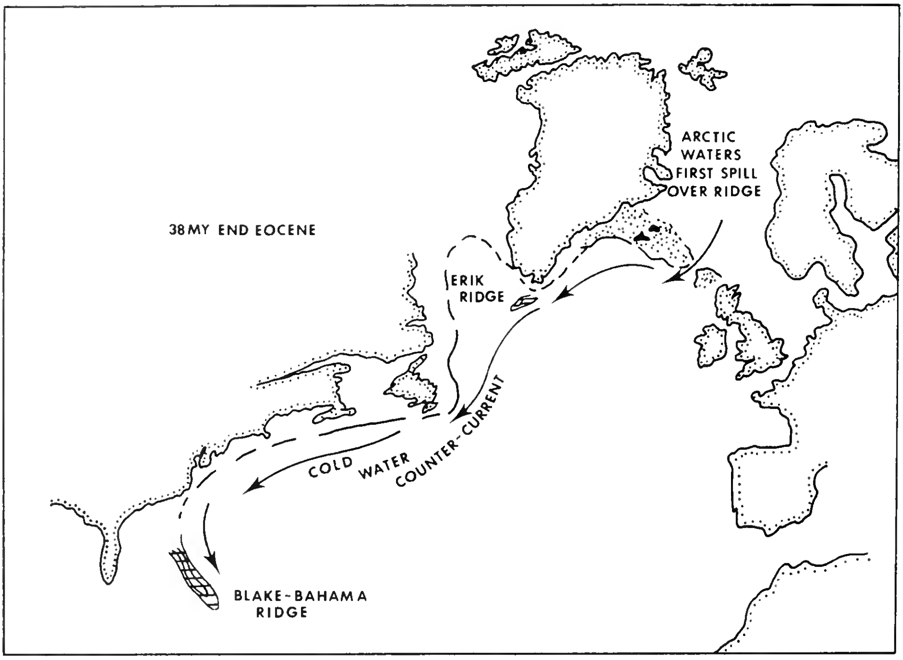


*Figure 7. Erosion of the deep continental margin off the eastern seaboard of the United States during the last 40 million years is attributable to a current of cold water spilling from the Arctic. The Iceland-Faeroes ridge (shown stippled with volcano symbols) was a barrier to this flow earlier. This is an example of how events in one part of an ocean can influence developments thousands of kilometers away. (© Copyright OTC, 1977)*

deposited farther offshore in the Blake-Bahama outer ridge (see page 40). Why did this happen? As Figure 7 shows, the deep current began to flow when cold arctic water first spilled over the Iceland-Faeroes ridge thousands of kilometers away. The spin of the earth kept the dense water flowing near the bottom on the western boundary of the ocean.

Atlantic-type margin studies are at an exciting stage. The first post-plate tectonic generation, using a simple rupture model, is over, and the second generation is beginning to develop, using the enormous amounts of data obtained through commercial and government-sponsored research. Deep structure is still a problem, and it may prove that resolution of the deep structure under the thickest of marginal sediment wedges will prove impossible. Then efforts will have to be concentrated on those areas where lack of sediment burial or exhumation has provided a window into regions that would otherwise prove inaccessible.

### Pacific-Type or Active Margins

These continental margins provide a great contrast to Atlantic-type margins. They are, as both Neville Donovan and Seiya Uyeda emphasize (see pages 63 and 52), areas of intense seismic, tectonic, and igneous activity, and it is these aspects that dominate active margin research. Petroleum exploration does not play as prominent a role as it does in research on Atlantic-type margins.

The association of active margins with places where inclined zones of earthquake foci indicate that slabs of lithosphere are descending into the mantle is well established, and so is an association with andesitic* volcanoes. Uyeda presents a full review of active margins, assessing the status of theories being used in attempts to understand their properties. A powerful influence on research on these margins has been the need to explain the occurrence of two kinds of convergent plate boundaries. In what Uyeda calls the Mariana-type, there is a marginal basin behind the volcanic arc within which the structure (see Figure 6, page 59) is very similar to that of a small Atlantic-type ocean. The edges of these marginal basins are rifted and resemble those of the Atlantic. In what Uyeda calls the Chilean-type, there is a continent behind the volcanic arc, which, in many places, crests a Cordilleran mountain belt.

In the last 10 years, many attempts have been made to explain the difference between the Mariana- and Chilean-type convergent boundaries. Most of these attempts, including my own, have not been particularly persuasive, but Uyeda and Hiroo Kanamori, as well as workers at the University of Minnesota and the Massachusetts Institute of Technology, have addressed the problem anew in the last year, attempting first to answer the questions: "What characterizes the boundaries with marginal basins and how do these

---

*Andesite is a volcanic rock composed essentially of andesine and one or more mafic constituents.

characteristics differ from the characteristics of Cordilleran margins?" As Uyeda shows in his article, formulating the right question has led to a leap forward in understanding.

### The Edges of Ancient Oceans

In 1965, J. Tuzo Wilson of the University of Toronto used the concept of plate tectonics as a way of describing the structure of the lithosphere, and as a means of accounting for tectonics that are active now. It also occurred to him, perhaps after he had recognized that the geology of Newfoundland showed that an ocean had opened and closed in the making of the Appalachian mountain belt, that just as the earth's surface today shows, through the action of plate tectonics, oceans opening in some places (for example, the Red Sea and the Atlantic), oceans wide open in others (the Pacific), and oceans closing in yet others (the Mediterranean), the history of the earth can be described in terms of complex cycles of the opening and the closing of oceans.

These cycles have come to be called eponymously "Wilson cycles." Mountain belts mark the places where oceans have closed, and I, for one, find romance in thinking of the lost oceans that have disappeared in making mountain belts like the Himalayas, the Urals, and the Appalachians. Evidence from northwestern Canada shows that processes of ocean opening and closing two billion years ago were apparently very similar to those of today, and many, though not yet all, accept that even the oldest rocks on earth (3.8 billion years old) were made under a similar regime of ocean opening and closing.

With the growing awareness of the geological complexity of modern oceans and their margins, which is reported in this issue, one wonders whether working out what happened in a fossil ocean that has disappeared and been replaced by a mountain chain might be altogether too difficult. This fear is not going to stop geologists. For at least two centuries, mountain belts have been their mecca. What they have found out is that although mountain belts are complex and the making of them has destroyed much of the record of their history, there are usually places in the mountains where at least part, often a substantial part, of the history can be deciphered. Suzanne O'Connell (see page 23) explains how certain critical associations of rocks are used in working out the history of the lost oceans in mountain belts. These rocks are the ophiolites, rocks formed on ocean floors and later thrust up into the mountain belts that have formed as the oceans closed.

### The Future Path

Ocean margins are places where geological understanding has leapt forward with the recognition of the plate structure of the lithosphere. This recognition has not only allowed formulation of general theories of margin origin and development, but also has encouraged the posing of numerous specific and readily addressed questions. At the same time, advances in geophysical technology, largely developed in connection with petroleum exploration, have permitted acquisition of large amounts of information of unprecedented quality from continental margins. The new hypotheses and the new data have together revealed the basic processes active in producing and developing ocean margins. Great diversity among these margins shows that the newly recognized processes have interacted in complex and, in some cases, unexpected ways. The challenge now is to study different continental margins, using a wide range of investigative techniques, and to work out individual histories. This challenge is beginning to be met in such studies as those reported by Schlee, Ross, and McCoy in this issue.

*Professor Kevin Burke is Chairman of the Department of Geological Sciences at the State University of New York at Albany.*

#### References

Boillot, G. 1979. *Geologie des marges continentales.* Paris: Masson.

Bott, M.H.P. 1976. Sedimentary basins of continental margins and cratons. *Developments in Geotectonics* 12. Amsterdam: Elsevier.

Bullard, E.C., J. Everett, and A.G. Smith. 1965. The fit of the continents around the Atlantic: In *Symposium on continental drift*. Phil. Trans. Roy. Soc. London 258A, 41-51.

Burk, C. A., and C. L. Drake. 1974. *The geology of continental margins,* New York: Springer-Verlag.

Burke, K. 1975. Atlantic evaporites formed by evaporation of water spilled from Pacific, Tethyan and southern oceans. *Geology* 3: 613-616.

Charpal, O.de, P. Guennoc, L. Montadert, and D.G. Roberts. 1978. Rifting, crustal attenuation, and subsidence in the Bay of Biscay. *Nature* 275, 706-711.

Pitman, W.C., III. 1978. Relationship between eustacy and stratigraphic sequences of passive margins: *Geol. Soc. America Bull.* 89: 1389-1403.

Wilson, J.T. 1965. A new class of faults and their bearing on continental drift. *Nature* 207: 343-47.

Wilson, J. T. 1966. Did the Atlantic close and then re-open? *Nature* 112: 676-81.

———. 1968. Static or mobile earth — the current scientific revolution. In *Gondwanaland revisited.* Am. Philos. Soc. Proc. 112: 309-20.

# Continental Margins: Geological and Geophysical Research Needs and Problems

*In June of this year, an ad hoc panel established by the Ocean Sciences Board of the National Research Council issued a report on the geological and geophysical research needs and problems of continental margins. The following extracts are from that report–* **The Editors.**

. . . Today, the earth sciences are especially concerned with continental margins. In the past, people regarded the seashore as the margin of a continent. Since the 19th century, marine surveyors have discovered extensive underwater terraces and slopes. These became the continental margins of the oceanographers. However, geologists working on land have long been aware of sea-level changes through the ages. They consider the present level of the sea to be an ephemeral coincidence.

Modern earth scientists are beginning to take a more comprehensive view of continental margins — one that encompasses a wide transition zone that separates oceanic from continental realms. The zone includes the continental shelf, slope, and rise, but it also embraces the landward extension of this geologic province. Thus, continental margins have now become the joint concern of scientists working on land and their colleagues who work in the oceans.

The continental margin is the place where land scientists meet ocean scientists, where sedimentologists meet physical oceanographers, where stratigraphers meet geophysicists, where economic geologists meet environmentalists, where industry meets government, and where government meets academe . . .

. . . Passive continental margins are those without significant concentrations of seismic and volcanic activity. They are located within a plate on the transition between continental and oceanic crust. These margins form at divergent plate boundaries. With time, they move away from those boundaries and become sites of massive subsidence and thick accumulations of sediment.

Cratonic margins lie entirely on continental crust. Strictly speaking, they do not qualify as transition between continental and oceanic crust. They do, however, occupy large areas covered by seas. Cratonic margins also may contain thick sediment accumulations.

Active margins are associated with intensive earthquake activity and spectacular volcanism. These margins form at convergent plate boundaries, that is, where rigid lithospheric plates are sinking deep in the more viscous asthenosphere of the earth or where plates move laterally with respect to each other. Differential uplifts and downwarps on active margins lead to the formation of mountain ranges and small, but deep, sedimentary basins. Most characteristic of convergent active margins is the formation of island arcs, with marginal basins developing on their concave side.

Sedimentary basins belonging to all continental-margin types are sites of oil and gas accumulations. Significant amounts of oil and gas trapped in these basins remain to be discovered. Other mineral resources of continental margins include sand and gravel, heavy minerals (such as cassiterite, diamonds, gold, and barite), phosphates in shallow water depths, and manganese nodules at greater depths . . .

. . . A stepped-up effort in solid-earth research on continental margins is desirable, because without scientific underpinnings we cannot properly evaluate and manage resources of these margins. Because all resource exploitation affects the surrounding environment, we should also try to understand that environment.

Erosion and sedimentation mold the surface of continental margins. On coasts, these processes have been studied for many years. In the past, sedimentologists have made surveys of the sediment distribution on continental margins. The next task is to go beyond these studies and try to understand the processes that dictate the entrainment, transport, and deposition of sediments in coastal areas and on the shelf, slope, and rise. We know there are complex currents sweeping over the continental margins, but we know little of their spatial distributions. Physical oceanographers have made great advances in modeling these currents, but many theoretical aspects are not fully understood. Most of the concepts have not been tested. We need to measure the capacity of these currents to erode and to carry sedimentary particles in order to understand the details of sediment settling and deposition.

In order to apply what we learn of sediment settling and deposition, we must reconstruct conditions of the geological past. We now better understand how sea level has changed by amplitudes of more than a hundred meters during glacial versus nonglacial epochs of the Pleistocene. With these changes of sea level, continental shelves have been alternately exposed and inundated. The last rise of sea level was so recent that sediment distributions have not yet come into equilibrium with environmental conditions. To apply the principles of distribution and deposition of sediment on continental shelves, we ought to understand fully how the processes we observe today differ from those that were prevalent during other geological times . . .

. . . Passive continental margins are now recognized to be the modern equivalent of some of the old geosynclines. During the last decade, we have learned that the deeper portion of passive margins conceals an early rifting history that preceded the actual opening of the ocean. Geologists infer much from seismic lines, but in fact, there are few places where the early rifting sequence has been documented in detail by seismic lines that are calibrated by drilling evidence. Such studies could greatly improve our understanding of the restricted early rifting environments visualized by geologists. These environments sometimes lead to the deposition of salt and organic-rich source beds, which can be critical factors in determining and explaining the presence or absence of hydrocarbons on passive margins.

Geophysical models portray the evolution by subsidence of passive margins as the consequence of crustal cooling combined with sediment loading. To confirm the validity of these models, we need reliable subsidence data based on wells not located on structural anomalies.

A vexing problem on both active and passive margins is the nature of the ocean-continent boundary and its associated gravity and magnetic anomalies. Multichannel seismic techniques combined with refraction seismic methods have improved the geophysical resolution of the continent-ocean boundary. The answers to some aspects of this problem await testing by the drill in locations that are carefully selected after much geophysical work. However, a basic understanding of this problem will require the application of geophysical methods capable of resolving lateral variations in upper-mantle structure extending to several hundred kilometers depth.

Major problems in geology remain to be solved on active margins. Plate boundaries were initially defined by the distribution of earthquakes. In some cases, two plates slip laterally past each other (San Andreas Fault), while other cases (e.g., island arcs of the West Pacific) suggest that a cold lithospheric slab is sinking under another lithospheric plate. First-motion studies of earthquakes suggest that some segments in the sinking slab are under compression and that others are under extension. Often, these studies lack detail and precision. The use of ocean-bottom seismometers (OBS) allows much more detailed studies of microearthquakes on a more local scale and should greatly help augment existing data. The same instruments, used for refraction profiling, allow us to study the nature of the lower crust and the upper mantle on active margins.

The study of earthquake dynamics is an especially important aspect of continental-margins research. Emphasis should be placed on investigating the tectonic stress regime of the margins. Digitally recording global networks of seismometers and OBS's will be useful for this purpose. This research is directly relevant to earthquake forecasting.

Seismic-reflection data suggest that great wedges of structurally deformed sediments exist on the inner side of deep-sea trenches. These are believed to be sediment scraped off the top of deep-sea trenches. Only a few wells have penetrated the top of these sequences. Here again, deep drilling based on carefully planned geophysical surveys will help in explaining the genesis of these frontal zones of island arcs.

As we move landward from the deep-sea trenches, we observe extensive volcanic arcs. Farther inland, we encounter their deep-seated equivalents, the igneous intrusions, which have been uplifted during complex, mountain-building events. Geoscientists now realize that active margins are the places where mountain building can be caught in the act. A large data gap separates the deep-earth information given by seismologists from the surface data gathered by surface geologists and geochemists.

To close this gap, we need crustal refraction and reflection studies both on the oceans and on land. Current progress in deep crustal reflection work on land is particularly encouraging. This work should be the foundation for crustal drilling on land that would complement the marine margin drilling planned for the International Phase of Ocean Drilling (IPOD) . . .

. . . The essence of our thinking is that (a) the time is ripe to concentrate more research on domestic continental margins, (b) the best geological and geophysical technology should be used for such research, and (c) drilling for scientific purposes can be justified only if it is preceded by detailed geological and geophysical surveying.

We attempted to compare expenditure levels for solid-earth continental-margins research with past expenditures but were unable to isolate the relevant figures from the multitude of budgets from federal agencies and academic institutions. The levels of expenditure we propose are high. ($41 to $50 million a year over the next decade in 1977 dollars, plus a possible additional $350 million in drilling costs — **ed.**) Our most expensive recommendations (i.e., first priority, two geophysical vessels; and, second priority, drilling) address primarily the problems of data quality and, to a lesser degree, increases in the pace of gathering or volume of data. Consequently, the number of people working on continental margins on land and at sea may not increase proportionately to the increased expenditures.

Science — and particularly oceanography — is international. However, we believe that an effort with increased emphasis on national concerns is needed. The scientific problems are there in abundance, and to remain leaders in the international field, we must couple the best technology and a strongly developed understanding of our own efforts with efforts undertaken by our North American neighbors. There, we must be mindful of the obvious: Our neighbors have their own style of work on their resources and their environment. We should not take them or their cooperation for granted. However, we do share the same resources and environmental concerns and, therefore, should also share the fruits of our mutual research.

We recommend that these goals for geological and geophysical research on continental margins be part of an overall research plan for the 1980's that addresses the evaluation of resources and the management of the environment of North America and its surrounding seas — in short, the North American natural heritage. We are recommending an increase in the momentum of solid-earth science research in our own backyard . . .

*The full report of the panel (302 pages) is available from: Office of Publications, National Academy of Sciences, 2101 Constitution Avenue, N.W., Washington, D.C. 20418. Price $16.25.*

# Assessing Oil and Gas Resources

*A bright flare signals that natural gas has been discovered in the Baltimore Canyon trough. Strike on wildcat rig was made by Texaco and five other companies on August 13, 1978, on Outer Continental Shelf, about 100 miles off Atlantic City, New Jersey. (Photo courtesy Texaco)*

# on the U.S. Continental Margin

## by N. Terence Edgar and Kenneth C. Bayer

Six years have passed since the eye-opening oil embargo of 1973 — six years of frantic evaluation of the country's prime energy source, environmental hassles, and litigation. Even the most cursory examination of our progress to seek new sources of oil and gas reveals a high level of frustration among all parties concerned, and a discouragingly low level of success.

As a result of the embargo, the Department of the Interior established an offshore leasing program that focused on the frontier Outer Continental Shelf (OCS) areas (Figure 1). The Gulf of Mexico, as shown in Figure 1, is not considered a frontier area, although as an offshore area it was assessed for oil and gas. An accelerated leasing schedule was issued by the Department of the Interior in June of 1975, and it was modified in June of 1977. A schedule of proposed sales currently is being prepared for release this year.

To date, six lease sales have been held in these frontier areas. One lease sale was tied up in litigation (Georges Bank), and drilling was delayed for more than a year and a half in another lease sale (Baltimore Canyon trough). As of June 1979, 40 wells have been drilled on leases issued in these frontier areas. A total of $2,594,299,909.42 (not including the June, 1979, California Sale, No. 48) has been paid for leases by industry, but no commercial quantities of oil have been found.

An assessment of the oil and gas prospects in a frontier area, before the sale is held and exploratory drilling commences, is a fundamental part of the offshore leasing process. The user must have confidence in these estimates if they are to be of value in establishing policy or conducting a

*Figure 1. The frontier Outer Continental Shelf areas (excluding the Gulf of Mexico) of the United States.*

leasing program. Confidence depends upon reliability and credibility. Reliability of resource estimates implies accuracy. Credibility depends upon the user's confidence in the data set, the adequacy of the systematics of data manipulation, and the application of geologic wisdom.

All too often oil and gas resource estimates have been taken with too much faith and too little understanding of how they are generated and what they represent. It has been suggested that, because assessments are given in barrels of oil and cubic feet of gas, they are accurate to the point of being misleading, and that, instead of estimating the resources of an area in barrels of oil and cubic feet of gas, an assessment should be based on an arbitrary logarithmic scale. For example, the scale could be set on the low end to fit the smallest known commercial oil and/or gas field, or to some small whole number. The high end would remain open. But, to be meaningful to the public, a scale must have some basis in reality. It could be a simple exercise to relate an arbitrary scale to the world's fields, which produce barrels of oil and cubic feet of gas. The important point is the intent of the exercise.

The intent of resource estimates is to convey an understanding of the resource potential of an area on the basis of available data, statistics, and the best scientific judgment. The results are only guidelines, but they are valuable in preparing for lease sales, estimating environmental and socioeconomic impacts, and forming a national energy policy.

### Key Terms Defined

Before proceeding, it is important to understand some key terms used by the U.S. Geological Survey (USGS) in making oil and gas assessments. Resources are defined as concentrations of naturally occurring solid, liquid, or gaseous materials in or on the earth's crust in such form that economic extraction of the commodity is currently or potentially feasible. Undiscovered recoverable resources are those economic resources that are estimated to exist in favorable geologic settings. Undiscovered recoverable resources are treated as uncertain quantities, the degree of uncertainty being expressed in the form of probabilities. It is desirable to report the probability that total recoverable resources are less than a given number or lie between two numbers. A reserve is the part of an identified resource that can be economically extracted using existing technology and whose amount is estimated from geologic evidence supported directly by engineering measurements (commonly referred to as proved reserves). From these definitions, clearly, no reserve figures can be given for frontier OCS areas; estimates are for undiscovered recoverable resources only.

Three fundamental methods have been used in estimating petroleum resources:

1. *Extrapolation of past experience, using such data as discovery rates and cumulative production. Techniques that employ historical data are not applicable to frontier areas.*
2. *Comparison of yields of oil and gas per cubic mile of sedimentary rock or square mile of surface area. In some cases, yields from geologically analogous basins have been compared with the unknown.*
3. *Analysis of combined geological and statistical models. These methods require a large amount of data, and sophisticated mathematical and computer methods.*

The USGS uses the second and third methods for frontier areas, and conducts a comprehensive comparison of the results to all known published estimates.

It must be recognized that regional assessment procedures are based fundamentally on subjective probability techniques. They incorporate geological and geophysical judgments and analyses of petroleum characteristics of large areas or basins by individuals who have a geologic understanding of the specific area.

We can take a closer look at the process by using the Baltimore Canyon trough (BCT) as an example. It is the dominant geological feature within the mid-Atlantic margin (Figure 2). This basin is not confined to the continental shelf (0-200 meters), but extends well into the continental slope (200-2,000 meters). The trough extends approximately 500 kilometers from Long Island (40 degrees latitude) to northeast of Cape Hatteras (about 36 degrees latitude). It is an arcuate basin subparallel to the shoreline with its widest part (150 kilometers) off Atlantic City, New Jersey. Maximum sediment fill (post-Paleozoic) occurs east of Cape May, New Jersey, where it is approximately 20 kilometers.

One of the fundamental data requirements in estimating oil and gas resources is the volume of sediment in a basin. In the Baltimore Canyon trough, the volume of sediment is sufficiently large (122,000 cubic miles [196,000 cubic kilometers], 0-2,000 meters water depth) that one can assume there is a very good possibility that some oil and gas are present. In comparison, this volume of sediment is only $^1/_{15}$ of the volume of sediment (1,900,000 cubic miles [3,000,000 cubic kilometers]) in the prolific Persian Gulf Basin. The volume of sediments in the frontier areas of the OCS is 1,337,000 cubic miles (2,150,000 cubic kilometers). Even counting our wildest optimism for the Baltimore Canyon trough, we can say with reasonable assurance that the United States' reliance on Middle East oil is not going to disappear. This information is of value to the nation.

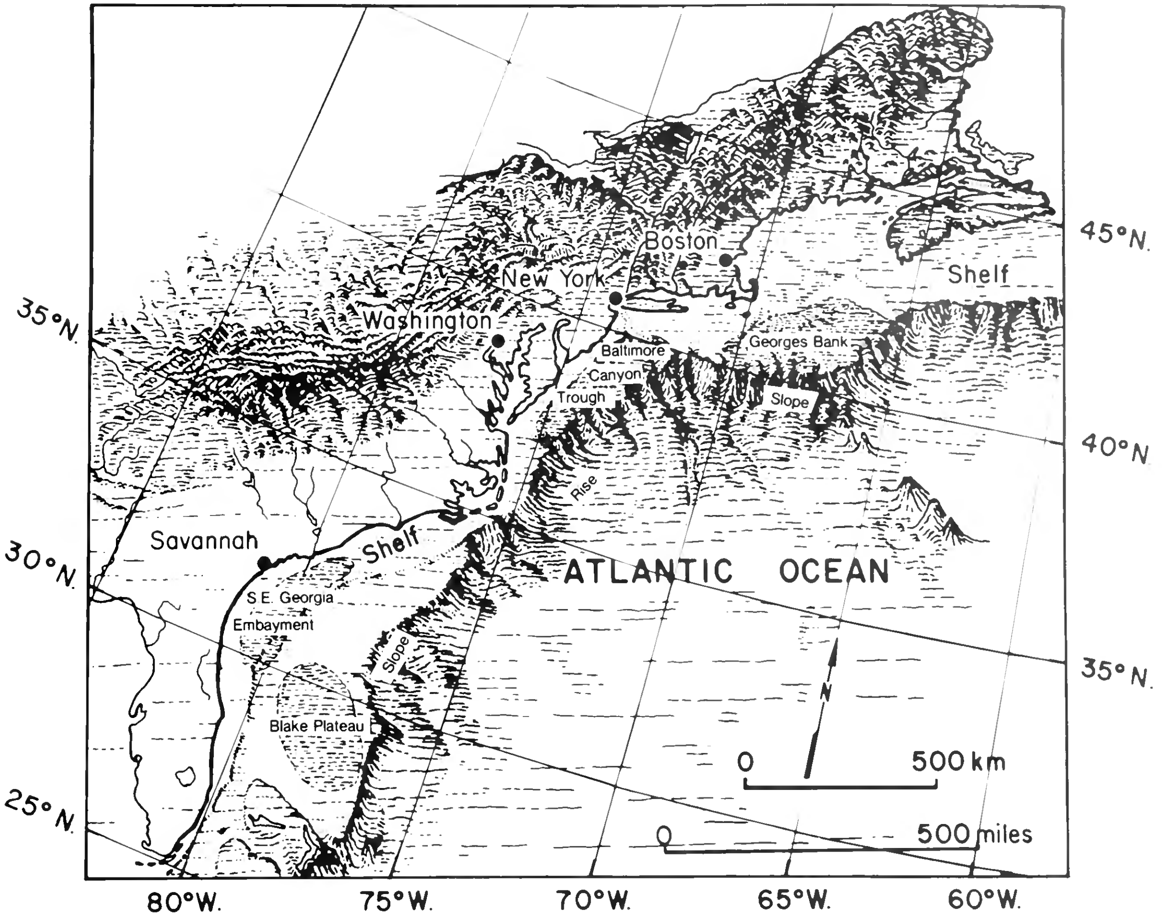


*Figure 2. The U.S. Atlantic continental margin, showing four lease areas — Georges Bank, Baltimore Canyon trough, the Southeast Georgia Embayment, and the Blake Plateau. The Baltimore Canyon trough contains the largest volume of sediment and has been regarded as the most promising prospect on the Atlantic margin.*

**Basic Conditions for Forming Oil and Gas**

The next step in assessing undiscovered resources is significantly more sophisticated; the application of geologic knowledge and understanding to the basin. The following eight fundamental conditions are required to form reservoirs of oil and gas:

1. *An adequate thickness (usually more than 2 kilometers) of sedimentary rocks.*
2. *A source rock that is rich in organic matter.*
3. *A suitable environment for the maturation of organic matter.*
4. *A favorable thermal history for the conversion of organic matter to oil and gas.*
5. *Porous and permeable reservoir rocks.*
6. *Adequate trapping mechanisms, such as folded or faulted rocks, or changes in permeability within sedimentary beds.*
7. *Favorable hydrodynamic conditions and suitable timing of petroleum generation and migration in relation to the development of traps.*
8. *Preservation of the hydrocarbons once formed.*

How can we assess these requirements for oil and gas accumulations in a basin that lies beneath the sea and has not been drilled? In the absence of geologic information, we must resort to analogs; compare the unknown with the known, and assess a range of probabilities.

In the Baltimore Canyon trough area, some information was available in 1974. Therefore, the initial step was to correlate offshore seismic reflection profiles with onshore drill holes and shallow offshore Deep Sea Drilling Project (DSDP) holes. A seismic profiling system is like a very powerful echo-sounder; a very low-frequency sound energy penetrates the ocean floor and reflects signals to the sea surface from layers of rock of contrasting density. The result is a record that looks like a cross section through a part of the earth. The system is excellent for outlining the geometry of the sedimentary basin and for locating structures (folds or faults in the rocks) where oil or gas may be trapped. These records tell us very little about the type of rocks in the basin, and nothing about their ages. But by relating the seismic reflectors to the rock sequence penetrated in a drill hole, we are able to "calibrate" or "ground truth" the seismic record in terms of geology.

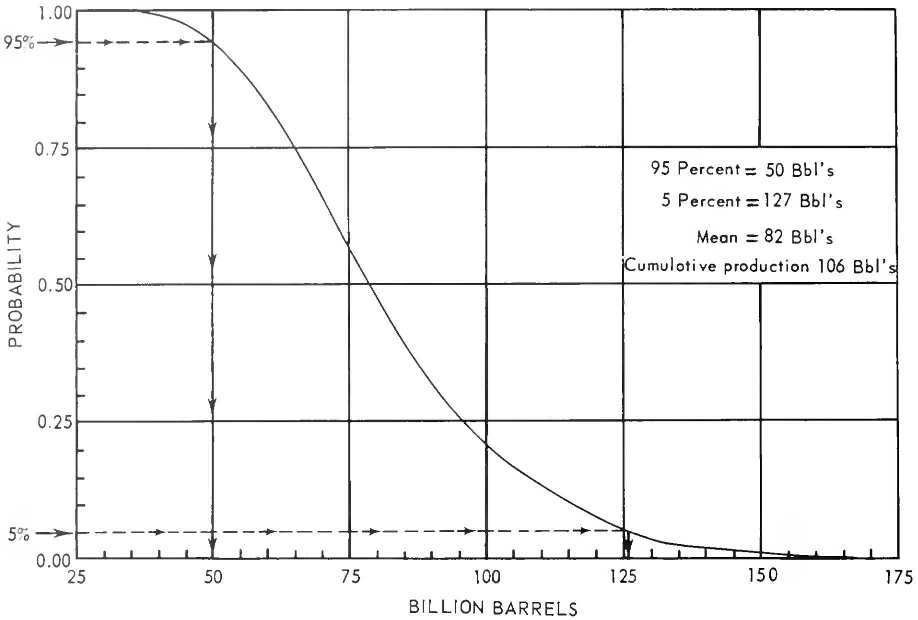


*Figure 3. Lognormal probability distribution of the undiscovered recoverable oil resources for the United States, onshore and offshore (0-200 meters).*

With a few geophysical lines and onshore wells, several analogs were selected for the Baltimore Canyon trough area; namely, the Scotian Shelf in eastern Canada and the Powder River basin in Wyoming; and for older sediments of Cretaceous age (70-130 million years), the provinces of southwest Alberta, Canada, and the Texas-Louisiana Gulf Coast. Analogs for the continental slope (deep-water areas) to evaluate possible carbonate reef rocks are the Edwards Limestone of Texas, and the Abra-Tamaulipas Formation of Mexico.

After reviewing all of the available data and assuming the occurrence of oil and gas in commercial quantities, a resource appraisal is made under the following categories:

1. *A low resource estimate, corresponding to a 95 percent probability that there is* ***at least*** *that amount.*
2. *A high resource estimate with a 5 percent probability that there is* ***at least*** *that amount.*
3. *A modal estimate of the resource that the evaluator decides has the highest probability of occurrence that there will be that amount.*
4. *Mean — a statistically generated number by adding 1, 2, and 3 above, and dividing by 3. (Monte Carlo techniques were utilized for aggregating the probability distribution of the sums of undiscovered oil and gas resources in regions consisting of more than one province and the probability distributions of the sums of the total undiscovered oil and gas resources.)*

The final probability distribution values are displayed in graph form in Figure 3 for the entire United States. On the graph, the 95 percent to 5 percent range represents the resources between a minimum value that is associated with a 19 in 20 chance that there is *at least* this amount and a maximum value that is associated with a 1 in 20 chance that there is *at least* that amount.

Since 1974, we have had the advantage of six years of geological and geophysical work on the Baltimore Canyon trough to enable us to assess its geological aspects with a greater understanding. Beginning in 1937 with seismic refraction studies and subsequent topographic studies and extensive sediment sampling, the Atlantic Outer Continental Margin (AOCM) of North America is presently considered one of the most extensively studied margins in the world. Although some continuous seismic reflection profiling was obtained in the early 1960s, it was not until the early 1970s that sophisticated, deeply penetrating seismic systems came into extensive use within industry and also through federally funded programs. Although no deep drill tests were made on the AOCM prior to 1975, sufficient geological and geophysical data had been acquired to make an estimate on the undiscovered recoverable oil and gas resources. Circular 725 of the U.S. Geological Survey, issued in 1975, included all available data from the North, mid-, and South Atlantic as a part of its offshore area assessments.

The Georges Bank basin, although apparently having a sufficient sediment thickness, was not rated as promising as the Baltimore Canyon trough because of the disappointing results of drilling on the Scotian Shelf in Canada. Although numerous offshore Triassic and Jurassic mini-basins are in evidence on Common Depth Point (CDP) seismic profiles, similar basins onshore are not indicators of oil and gas.

### The Great Stone Dome Disappointment

Of the three generalized Atlantic basins, the Baltimore Canyon trough of the mid-Atlantic was

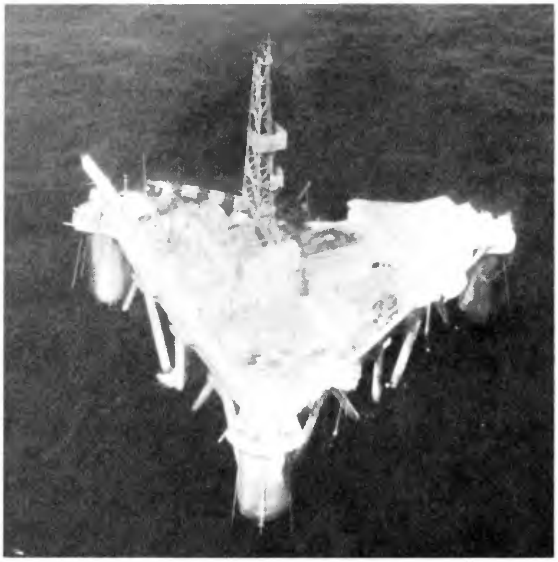
Table 1. Estimates of undiscovered recoverable oil and gas resources in U.S. offshore areas.

| AREA | CRUDE OIL (billions of barrels) | | | NATURAL GAS (trillions of cubic feet) | | |
|---|---|---|---|---|---|---|
| Water Depths of 0-200 meters (includes State and Federal lands) | 95% PROB. | 5% PROB. | STAT. MEAN | 95% PROB. | 5% PROB. | STAT. MEAN |
| 1. North Atlantic | 0 | 2.5 | 0.9 | 0 | 13.1 | 4.4 |
| 2. Mid-Atlantic | 0 | 4.6 | 1.8 | 0 | 14.2 | 5.3 |
| 3. South Atlantic | 0 | 1.3 | 0.3 | 0 | 2.5 | 0.7 |
| 4. MAFLA (Eastern Gulf of Mexico) | 0 | 2.7 | 1.0 | 0 | 2.8 | 1.0 |
| 5. Central Gulf of Mexico ) | 2.0 | 6.4 | 3.8 | 17.5 | 93.0 | 49.0 |
| 6. South Texas ) | | | | | | |
| 7. Southern California | 0.4 | 2.1 | 1.1 | 0.4 | 2.1 | 1.1 |
| 8. Santa Barbara Channel | 0.6 | 3.0 | 1.5 | 0.7 | 3.3 | 1.7 |
| 9. Northern California | 0 | 0.8 | 0.4 | 0 | 0.8 | 0.4 |
| 10. Washington-Oregon | 0 | 0.7 | 0.2 | 0 | 1.7 | 0.3 |
| 11. Lower Cook Inlet | 0.5 | 2.4 | 1.2 | 1.0 | 4.5 | 2.4 |
| 12. Gulf of Alaska | 0 | 4.7 | 1.5 | 0 | 14.0 | 5.8 |
| 13. Southern Aleutian Arc | 0 | 0.2 | 0.1 | 0 | 0.5 | 0.1 |
| 14. Bristol Bay Basin | 0 | 2.5 | 0.7 | 0 | 5.3 | 1.6 |
| 15. Bering Sea | 0 | 7.0 | 2.2 | 0 | 15.0 | 5.7 |
| 16. Chukchi Sea | 0 | 14.5 | 6.4 | 0 | 38:8 | 19.8 |
| 17. Beaufort Sea | 0 | 7.6 | 3.3 | 0 | 19.3 | 8.2 |
| Water Depths of 200-2500 meters | | | | | | |
| 4. MAFLA (Eastern Gulf of Mexico) | 0 | 1.9 | 0.5 | 0 | 1.2 | 0.3 |
| 5. Central Gulf of Mexico ) | 0 | 1.9 | 0.9 | 0 | 19.3 | 8.7 |
| 6. South Texas ) | | | | | | |
| 7. Southern California | 0.2 | 2.9 | 1.2 | 0.2 | 2.9 | 1.2 |
| 8. Santa Barbara Channel | 0.3 | 2.1 | 0.9 | 0.4 | 2.3 | 1.1 |

rated the highest as a potential source of hydrocarbons. The trough has the greatest thickness of sediments (up to 20 kilometers), a thick lower Cretaceous section, and a vast mafic intrusion known as the Great Stone Dome, with possibilities for structural and stratigraphic traps. Since the drilling of two Continental Offshore Stratigraphic Test (COST) wells in the BCT, plus 17 industry tests, new evaluations have been and continue to be made.

The Great Stone Dome, although not fully test-drilled as of this date, has been a costly disappointment, and will have an adverse effect on future resource assessments. Conversely, the results of drilling the COST B-3 slope test, plus significant gas shows and one oil show near the shelf edge on Lease Sale No. 40, should increase future estimate figures for the mid-Atlantic slope (200-2,000 meter water depth). The COST B-3 test recovered gas and favorable source rock material below 4,300 meters (14,000 feet), in sediments of Jurassic age. A Mesozoic shelf margin below the present continental slope may have the potential for commercial accumulation of hydrocarbons. Reef carbonate deposits associated with this paleoshelf edge may be of interest. Petroleum could have been generated in Early Mesozoic or Late Paleozoic facies and migrated up-dip (up inclined rock bedding) to reservoir rocks in the Mesozoic shelf margin.

The South Atlantic (southeast Georgia Embayment and Blake Plateau) frontier area received the lowest undiscovered oil and gas resource rating of the three AOCS areas (Table 1). Relatively thin sediment cover over most of the area combined with lack of significant structures on the shelf, plateau, and slope all contributed to the initial low resource assessment. The data from the COST GE-1 well did not enhance the earlier resource assessment of this area. In general, the sedimentary section penetrated by this well was thermally immature, suggesting poor source rock potential. However, potential reservoir rocks, with porosities in excess of 25 percent, were encountered. West of the COST GE-1 well, at the Blake escarpment, a reef began to develop during Late Jurassic time and grew upward before dying out in Early Cretaceous time. A broad carbonate platform developed behind this reef. If we assume that the older pre-Jurassic rocks contain source beds, subsequent migration of hydrocarbons may have taken place upward to the reef.



*The COST GE-1 rig. (Photo courtesy USGS)*

Figure 4 is a cross section of the continental margin through the BCT that is based on an interpretation of seismic records. It shows 14,000 meters of sediments and sedimentary rocks overlying the continental and ocean crustal basement rocks. The continental slope is the narrow zone with the steep gradient that joins the shelf and the rise. By collecting a number of such cross sections, the outline of the basin, the thickness of sediments, and the location and size of structures can be shown on a map. On the basis of an analysis of nine of these profiles within the western mid-Atlantic region, an isopach map was prepared (Figure 5) showing the distribution and thickness of the total sediment accumulation in the BCT. The contact between the sedimentary rock and acoustic basement is the deepest, most continuous band of seismic reflection energy that is mappable.

The sedimentary basins beneath the Scotian Shelf off eastern Canada contain thick sediments, and large structures have been located, but drilling results have been discouraging. In this province, thick sediments are intruded by salt structures similar to the productive salt dome province in the Gulf of Mexico, but other prerequisites for accumulation have not been met. One of these factors that has a bearing on the entire Atlantic seaboard is the thermal history of the area. The initial geologic history is common to the Scotian and U.S. Atlantic continental margin areas; namely that North America separated from Europe and Africa, and has continued to separate for the last 200 million years. Consequently, if the thermal history of the Scotian area was not generally favorable for the conversion of organic matter to gas and oil, then it is reasonable to assume the same might be true for the U.S. Atlantic margin.

Clearly, more knowledge about the geologic history and the nature of the rocks in the basin is required to substantially improve the accuracy of resource assessments.

### Future Prospects

In recognition of the need for more geologic information than can be obtained from seismic

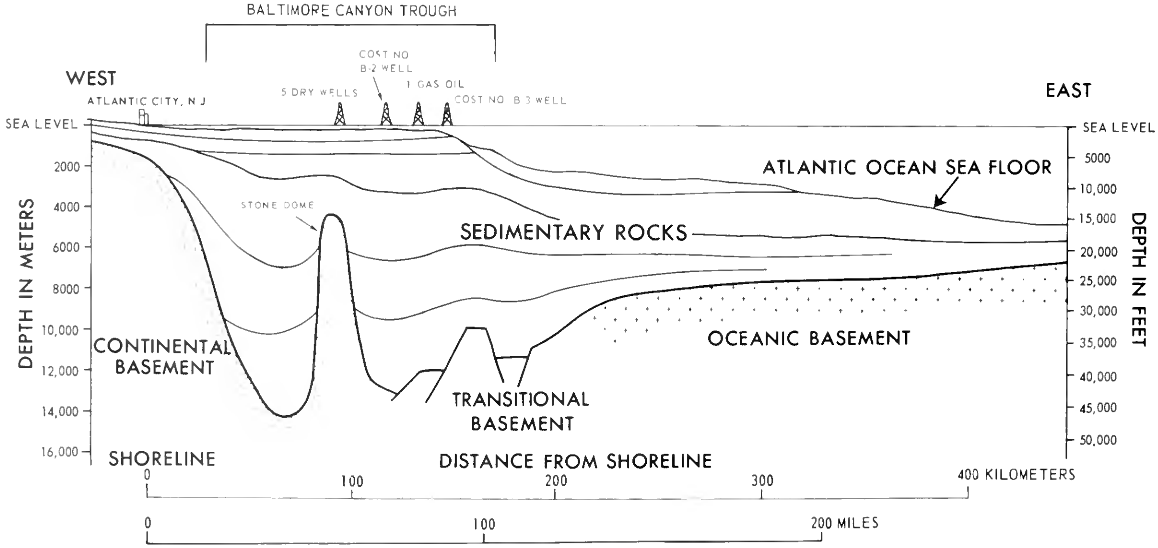


*Figure 4. Cross section of the Baltimore Canyon trough based on Common Depth Point (CDP) seismic reflection data. Tracts over the Great Stone Dome drew the highest bonuses at the first lease sale (40), reflecting industry's high interest in the potential of that structure.*

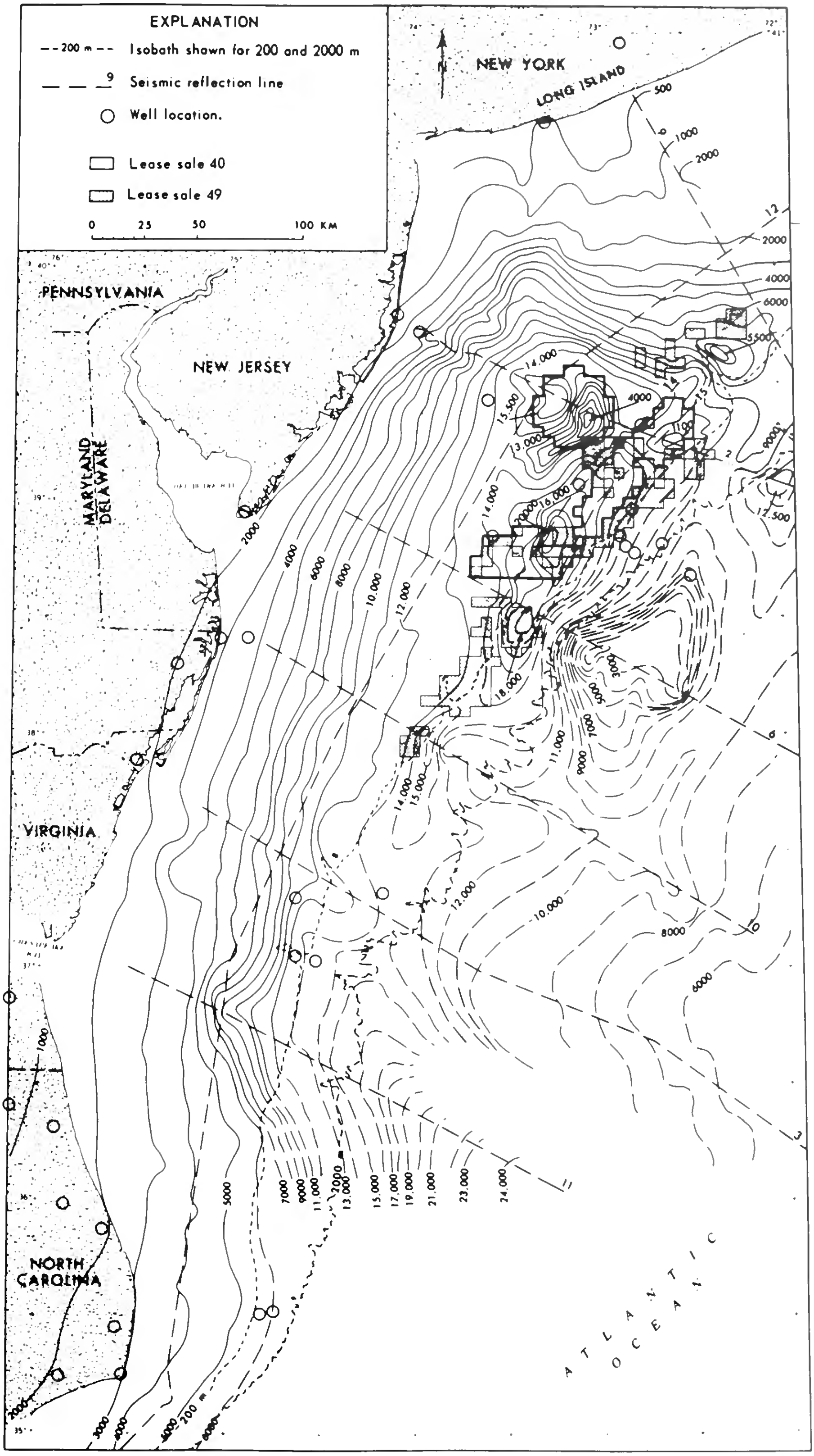


*Figure 5. Isopach contour map. Total sediments from sea floor to acoustic basement. Contour interval 1,000 meters, except part of Line 2 where the contour interval is 2,000 meters. Minimum or maximum contour closures are noted. Dashed contours indicate data are subject to change.*

Table 2. COST program stratigraphic test wells.

| Location | Well Name | Date Completed | Total Depth (ft) |
|---|---|---|---|
| Alaska, Gulf of Alaska | ARCO GOA COST #1 | 10 Oct. 75 | 5,150 |
| Alaska, Lower Cook Inlet | ARCO LOI COST #1 | 24 Sep. 77 | 12,387 |
| Alaska, Kodiak Shelf | ARCO KSSD — 1 | 18 Jul. 77 | 8,517 |
| Alaska, Kodiak Shelf | ARCO KSSD — 2 | 3 Sep. 77 | 10,460 |
| Alaska, Kodiak Shelf | ARCO KSSD — 3 | 25 Oct. 77 | 9,335 |
| Alaska, St. George Basin | ARCO SGB COST #1 | 1 Oct. 76 | 13,771 |
| California, Cortes Bank | ESC OCS-Cal 75-70 #1 | 2 Dec. 75 | 10,920 |
| California, Point Conception | Pt. Conception Test #1 | 18 Dec. 78 | 10,571 |
| Gulf of Mexico, Offshore Texas | COST #1 | 13 Nov. 74 | 15,763 |
| Gulf of Mexico, Offshore Texas | COST #2 | 19 Feb. 75 | 13,000 |
| Atlantic, Georges Bank | COST #G-1 | 26 Jul. 76 | 16,071 |
| Atlantic, Georges Bank | COST #G-2 | 31 Aug. 77 | 21,874 |
| Atlantic, Baltimore Canyon | COST #B-2 | 28 Mar. 76 | 16,043 |
| Atlantic, Baltimore Canyon | COST #B-3 | 25 Jan. 79 | 15,820 |
| Atlantic, Georgia Embayment | COST #GE-1 | 14 Jun. 77 | 13,254 |

records alone, industry formed a consortium of companies to pool their resources to drill stratigraphic test holes near prospective lease areas, but away from structures. Fifteen of these COST wells have been drilled to date (6 off Alaska, 2 off California, 2 in the Gulf of Mexico, and 5 off the Atlantic Coast [Table 2]). The information from these wells is available to the public 60 days after a tract has been leased within 50 miles of the site. If no tract is leased within 50 miles, the data are held proprietary by the consortium for two years.

COST wells provide an insight into geologic conditions that may reflect major trends that can be extrapolated by seismic means to large areas of the basin. In the BCT, the COST B-2 well was drilled seaward of the Great Stone Dome. The well contains a great thickness of sands and shales that include thermally immature (not enough heat to break down organic matter and generate oil and gas) organic material of continental origin, confirming earlier interpretations based on the Scotian Shelf drilling. Conversely, the BCT COST B-3 well had a thick sequence of organic shale (source rock) within the rocks of Jurassic age below 4,300 meters (14,100 feet). From this depth to the bottom of the hole at 4,823 meters (15,820 feet), a good gas source with high methane content was encouraging. The nature of the organic material and low thermal maturity suggest that there is a relatively low potential for the generation of oil, but there may be a potential for the generation of natural gas. Potential reservoir beds, exhibiting good porosity and permeability, are present throughout most of the sedimentary sections, except in the deepest part. A gas show was encountered at about 4,800 meters (15,750 feet).

In some areas, strata are exposed on the steep sides of the continental slope, seaward of the shelf. They can be sampled by dragging dredges along the bottom, picking up loose rock, and knocking off pieces of exposed bedrock. It is a hit-or-miss system and a far cry from the systematic evaluation obtained from the COST wells. However, in the absence of any other data, the effort can be very rewarding. For example, geophysicists at the U.S. Geological Survey had interpreted a feature on the seismic records as an ancient buried reef that extends along a major part of the eastern seaboard, but there was no direct evidence of reefs north of the Blake Plateau until scientists from the Lamont-Doherty Geological Observatory, using the deep submersible *Alvin*, recovered reef rock exposed in a canyon off Georges Bank. Confirmation of seismic interpretations is extremely valuable in assessing the resource potential of an area.

The first lease sale (No. 40) in BCT brought in $1.13 billion in royalty bonuses for the U.S. government, with most of this money spent for lease tracts centered around the Great Stone Dome, the biggest and most promising structure in the Atlantic OCS. To date, five wells have been drilled on this structure; all are dry and abandoned (Figure 6). The prospects were gloomy until Texaco encountered gas very close to the seaward edge of the continental shelf (Figure 6), but a subsequent well also drilled by Texaco just 3 miles to the west is dry. In June of this year, the first oil discovery off the

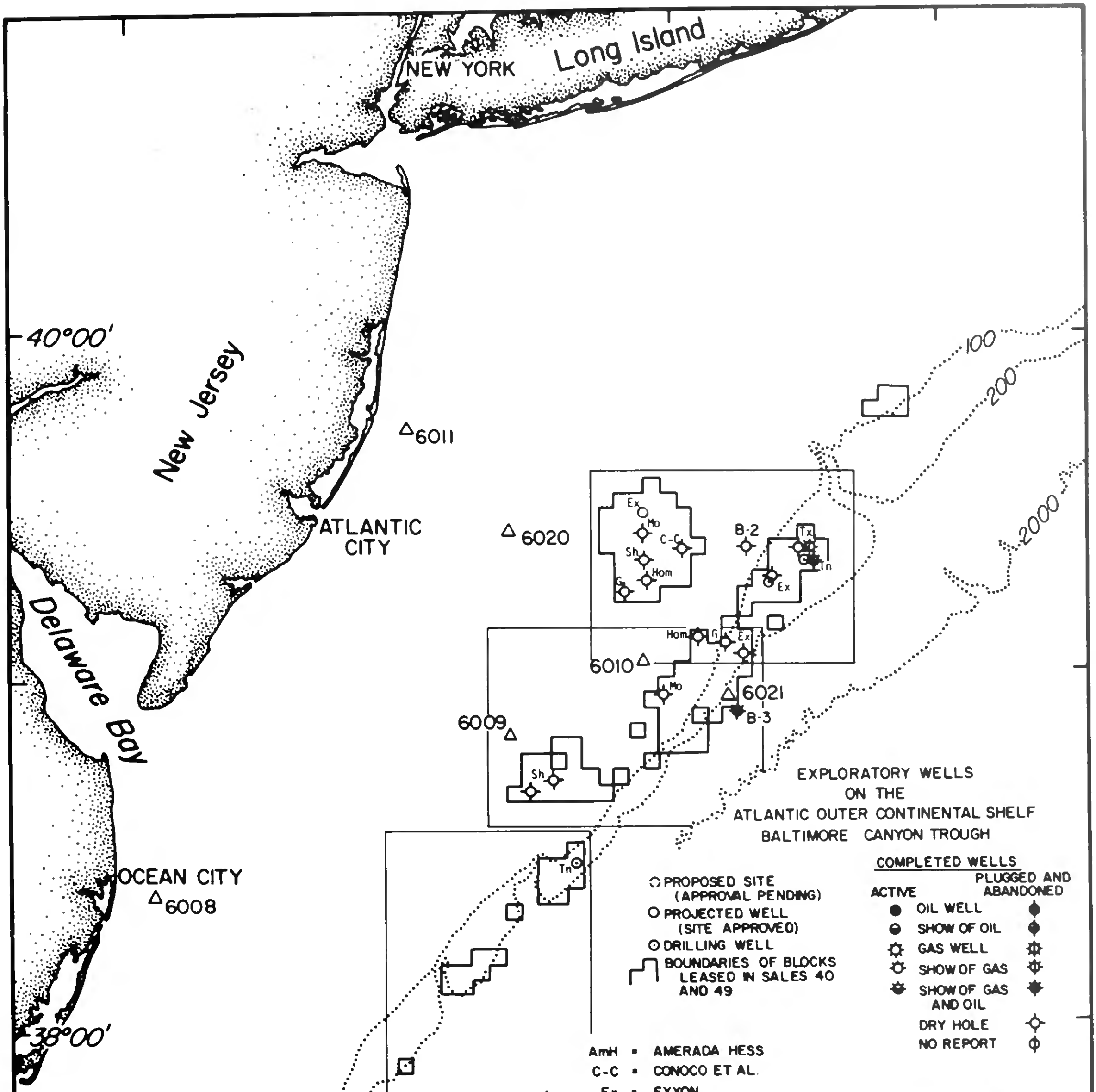


Figure 6. Lease boundaries for Lease Sale 40 and 49. Also locations of exploratory holes drilled by industry, Continental Offshore Stratigraphic Test (COST) wells, and shallow Atlantic Margin Coring Project (AMCOR) holes drilled by the U.S. Geological Survey in 1976. The five dry holes in the northwestern part are over the Great Stone Dome. The only discoveries to date are the Texaco well in Lease Block 598 (gas), the Tenneco well in Lease Block 642 (gas and oil), and the COST B-3 well (gas).

U.S. Atlantic coast was announced by Tenneco. The oil flowed at a rate of 630 barrels per day — not a threat to the OPEC nations, but significant because of its presence.

The seaward edge of the shelf may be where future drilling activity will focus, leaving the Great Stone Dome an expensive, disappointing prospect. The shelf-edge area is relatively small, as are the prospective geologic structures.

Seaward of the continental shelf off the Baltimore Canyon trough lies the continental slope and rise, which are underlain by great thicknesses of sediment. Seismic surveys have demonstrated that this apron of sediment extends from Canada to the Bahamas and, therefore, constitutes an area of major proportions, possibly containing oil and gas. Very large structures that could serve as traps for hydrocarbons have been identified, but at present there is no evidence that such reservoirs exist. For that matter, we have little more to go on than speculation regarding the nature of rocks and the geological history of this region.

As previously mentioned, seismic reflection records indicate the presence of a linear structure that underlies the slope and is parallel to the shelf edge throughout a major part of the U.S. Atlantic margin. It is believed to be a reef that existed about 130 million years ago (Berriasian). Reefs are known for their porosity and reservoir characteristics. Unfortunately, this reef is exposed to the sea at least at one location on Georges Bank, rendering it an unlikely target for future exploration in that area. If in the past the reef was exhumed along other parts of the continental slope, the petroleum prospects for the outer margins could be reduced substantially. Geologists must factor this unknown condition into future resource estimates.

The only evidence for the presence of source rocks seaward of the continental shelf comes from the COST B-3 well and drilling in the deep part of the western Atlantic basin by the deep-sea drilling vessel *Glomar Challenger*. At several widely spaced drill locations, ancient organic-rich clays were recovered. Although the organic material is primarily of continental origin and thermally immature, the clays could constitute a source of gas deeply buried beneath the continental slope and rise, provided that the thermal regime has been favorable. The clay interval identified at the drill site can be traced seismically to the reef complex, but there is no assurance that the sediment interval beneath the slope and rise contains the organic matter found at the drill site. If the organic-rich layer does abut the reef, then the prospects of finding substantial gas (or possibly oil) are much enhanced.

According to the drilling and the geologic understanding to date, the most favorable oil and gas prospects in the Baltimore Canyon trough are beneath the outer part of the continental shelf and beneath the continental slope.

Although exploration has been disappointing around the Great Stone Dome, favorable indications of oil and gas are being found beneath the outer part of the continental shelf. If the reef that lies beneath the continental slope contains petroleum, it could represent a resource of major proportions and encourage deep-water exploration in other continental margin areas.

*N. Terence Edgar is Deputy Chief for Marine Geology, U.S. Geological Survey, Reston, Virginia. Kenneth C. Bayer is a geophysicist, in the USGS Branch of Oil and Gas Resources at the same location.*

**Selected References**

Emery, K. O., E. Uchupi, J. D. Phillips, C. O. Bowin, E. T. Bunce, and S. T. Knott. 1970. Continental rise off eastern North America. *AAPG* 54(1): 44-108.

Emery, K. O., and E. Uchupi. 1972. Western north Atlantic ocean: Topography, rocks, structure, water, life and sediment. *AAPG* Memoir 17.

Mattick, R. E., O. W. Girard, Jr., P. A. Scholle, and J. A. Grow. 1978. Petroleum potential of U.S. Atlantic slope, rise, and abyssal plain. *AAPG* 62(4): 592-608.

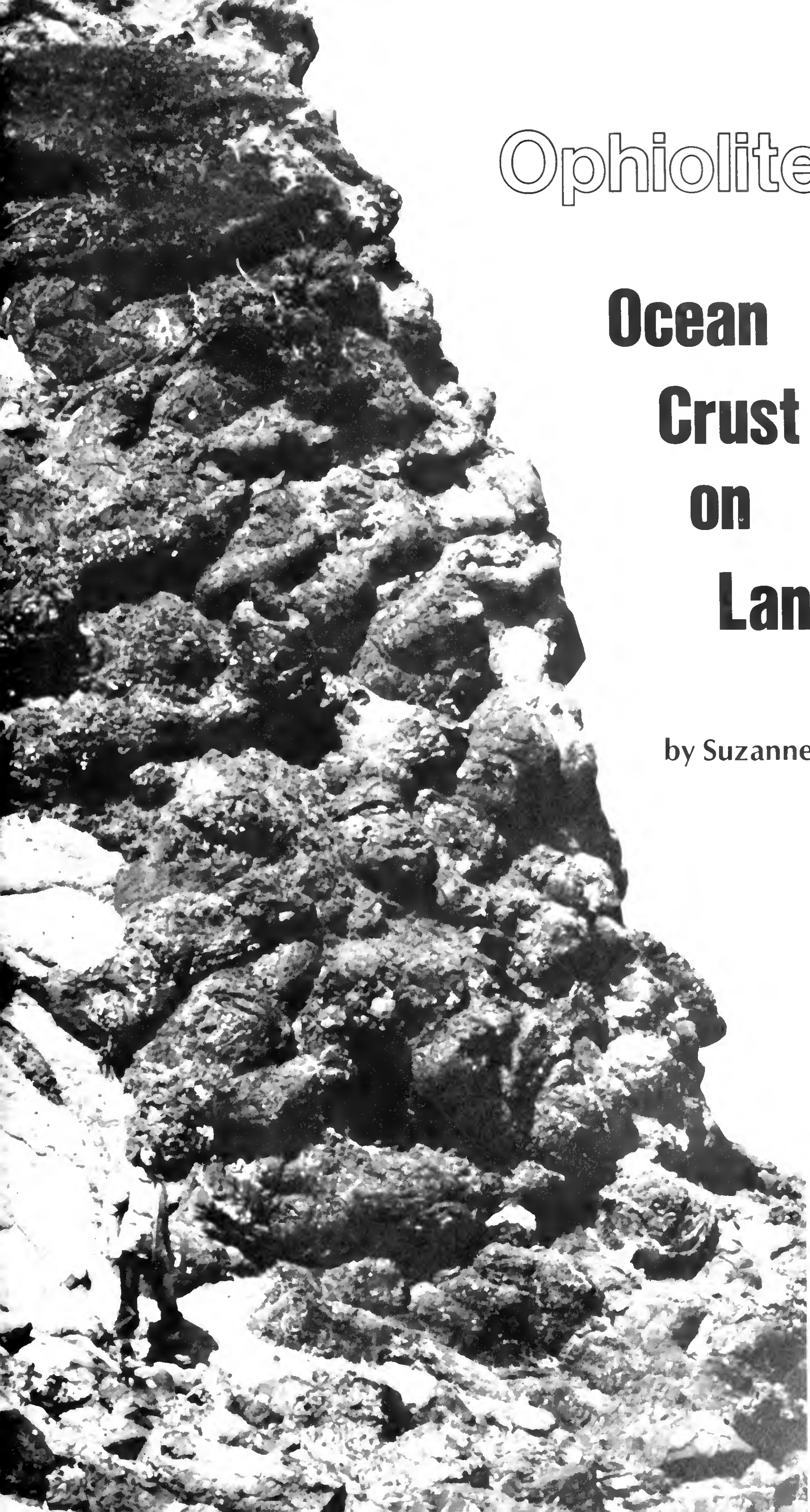
Miller, B. M., H. L. Thomsen, G. L. Dolton, A. B. Coury, T. A. Hendricks, F. E. Lennartz, R. B. Powers, E. G. Sable, and K. L. Barnes. 1975. Geological estimates of undiscovered recoverable oil and gas resources. In *USGS Circular 725.*

Ryan, W. B. F., M. B. Cita, E. L. Miller, D. Hanselman, W. D. Nesteroff, B. Hecker, M. Nibbelink. 1978. Bedrock geology in New England submarine canyons. *Oceanologica Acta* 1(2): 233-54.

Schlee, J. S., J. C. Behrendt, J. A. Grow, J. M. Robb, R. E. Mattick, P. T. Taylor, and B. J. Lawson. 1976. Regional geologic framework off northeastern United States. *AAPG* 60: 926-51.

## Correction

*In last issue's article "Galápagos '79: Initial Findings of a Deep-Sea Biological Quest," the credit line was inadvertently dropped from the scanning electron micrograph photographs appearing on pages 8 and 9. They were taken by Carl O. Wirsen and Holger W. Jannasch.*



# Ophiolites:

# Ocean Crust on Land

by Suzanne O'Connell

*Vertical section of pillow basalts exposed along the coast of western Newfoundland in the Bay of Islands ophiolite complex.*

The ocean floor is ephemeral, continually being created at mid-oceanic ridges and consumed at subduction zones. The oldest ocean crust was formed only 200 million years ago, representing 5 percent of the earth's history. Parts of the continental crust, on the other hand, have endured most of the earth's 4.5-billion-year history. The fundamental differences between continental and oceanic crust go far beyond age. The composition, age, and structural relationships of their rock foundations are different. Oceanic crust averages between 5 and 7 kilometers in thickness, and has a relatively simple composition that is continuous throughout most of its length. Continental crust is not as easily described. Its complex architecture consists of enormous blocks of rock, varying in thickness (15 to 40 kilometers) and composition, that are slowly being assembled and bound together.

Among the rocks found on continents are ophiolites. Ophiolite (ōf′ ē ō līt), a word seldom heard outside of the geologic community, refers to a specific assemblage of rock types. The resemblance between ophiolites and what is known about ocean crust (from seismic probing, drilling, dredging, and observations from submersibles) is so strong that ophiolites are thought to be huge slabs of oceanic crust that broke off subducting ocean crust (see page 52) and were pushed onto continents and island arcs (Figure 1). As fragments of ocean crust, ophiolites hold intriguing scientific information about the location of ancient oceans and the formation of ocean crust. They also can be the site of important mineral deposits.

### Ancient Oceans on Land

Ophiolites do not occur as isolated slabs, but are part of an assemblage of rock types found landward of active subduction zones, such as Japan and Chile, and in major geosutures (long, linear mountain ranges created by continental collisions), such as the Alps and Appalachians (Figure 2).

In the middle of the 15th century, the Swiss naturalist Felix Hemerli noted that some fossils found in Alpine rocks, far from the sea and thousands of meters above sea level, were organisms that had once lived in an ocean. Later, geologists working in the Himalayas — containing the highest mountain peaks on earth — found marine fossils from the Triassic period (about 200 to 230 million years ago). Since these discoveries, it has become evident that virtually all the world's

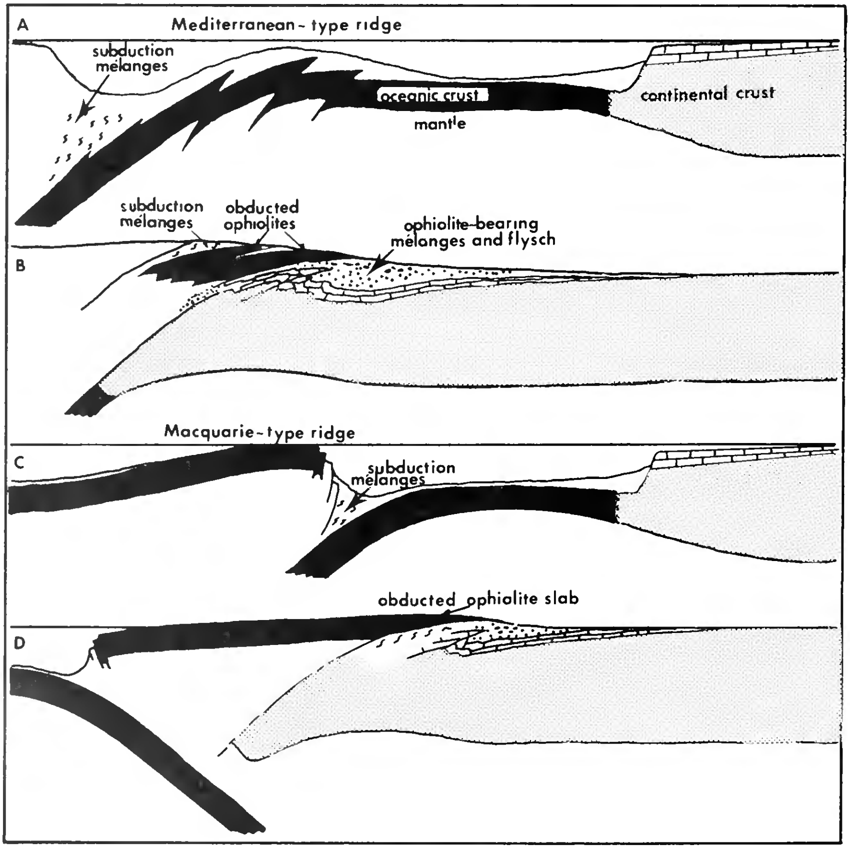


*Figure 1. A subduction zone with slabs of oceanic crust being broken off and emplaced on a continent.*

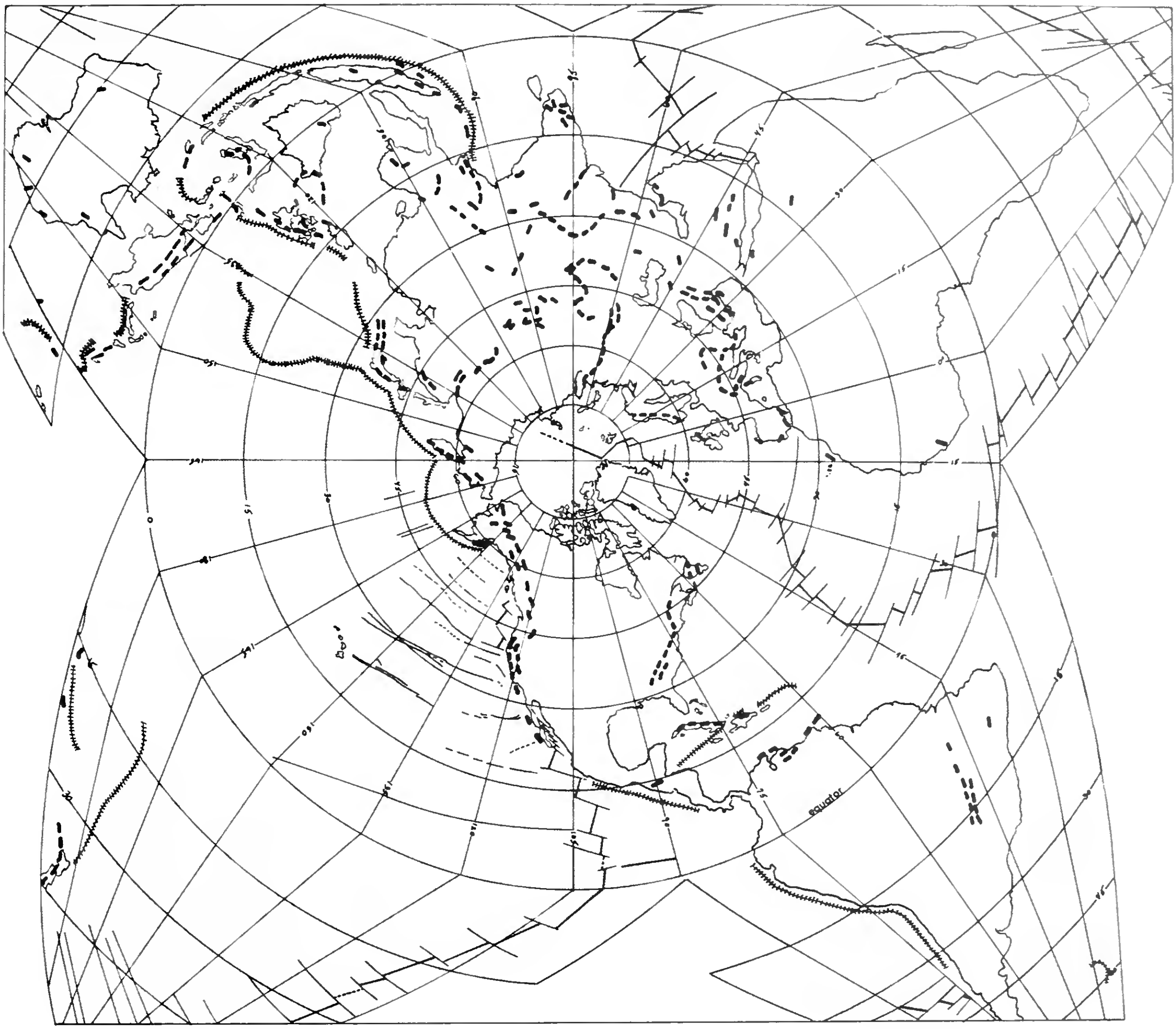


*Figure 2. The principal ophiolite belts of the world. (From W. P. Irwin and R. G. Coleman, USGS, 1974)*

important mountain ranges contain large amounts of these fossils and sediments, and occasionally ophiolites, fragments of oceanic crust. These ophiolites are often much older than any ocean crust presently found in the oceans. Some ophiolite fragments may have formed in the pre-Cambrian period (more than 570 million years ago). This raises the question — How did the ophiolites become part of continental mountain belts?

The mystery began to unravel early in the 20th century with the publication of Alfred Wegener's *The Origin of Continents and Oceans*, in which he proposed a comprehensively developed theory of continental drift — the notion that the continents of the world were once joined as a single land mass (Pangaea) and then split and drifted apart. He believed the continents were akin to giant barges — that the earth's crust was, in a sense, afloat. This was a further step in the evolution of geological thinking that only a century earlier had been freed from the clerical tenets that catastrophes — such as floods — had brought about sudden and radical changes in the earth's surface. The change in thinking occurred with James Hutton's doctrine that "the present is the key to the past" — the forces we see at work today are those that existed in the past — often referred to as the principle of uniformitarianism.

Where the process of mountain building was concerned, geology was dominated by the concept that they were formed by a shrinkage of the earth, similar to the wrinkles on a dried apple. Some geologists, such as Clarence Dutton of the U.S. Geological Survey, pointed out that shrinking would produce very irregular topography, and not linear mountains. Concurrent with Dutton's observations was the discovery of radioactivity at the end of the 19th century. This further disproved the shrinking earth hypothesis. Radioactive elements within the earth generate heat during their decay. Since the earth had not cooled a great deal over time, it could not be shrinking.

# GEOLOGIC TIME

| TIME DIVISION | | | YEARS AGO | MAJOR GEOLOGIC DEVELOPMENTS |
|---|---|---|---|---|
| CENOZOIC ERA | QUATERNARY PERIOD | RECENT | 10,000 | GREAT LAKES |
| | | PLEISTOCENE | 2 million | NORWEGIAN FJORDS<br>ICE AGES |
| | TERTIARY PERIOD | PLIOCENE | 5 million | BLACK SEA<br>CASPIAN SEA |
| | | MIOCENE | 22 million | HIMALAYAS |
| | | OLIGOCENE | 38 million | ALPS |
| | | EOCENE | 55 million | |
| | | PALEOCENE | 65 million | ANDES MOUNTAINS<br>ROCKY MOUNTAINS |
| MESOZOIC ERA | CRETACEOUS PERIOD | | 135 million | CHALK DEPOSITS<br>COAST RANGES |
| | JURASSIC PERIOD | | 180 million | SIERRA NEVADA<br>JURA MOUNTAINS |
| | TRIASSIC PERIOD | | 225 million | NEW JERSEY PALISADES<br>CAUCASUS |
| PALEOZOIC ERA | PERMIAN PERIOD | | 270 million | URAL MOUNTAINS<br>APPALACHIAN MOUNTAINS<br>POTASH DEPOSITS |
| | PENNSYLVANIAN PERIOD | | 300 million | COAL DEPOSITS |
| | MISSISSIPPIAN PERIOD | | 350 million | |
| | DEVONIAN PERIOD | | 400 million | ACADIAN MOUNTAINS |
| | SILURIAN PERIOD | | 440 million | NIAGARA FALLS CAPROCK |
| | ORDOVICIAN PERIOD | | 500 million | TACONIC MOUNTAINS<br>LIMESTONE DEPOSITS |
| | CAMBRIAN PERIOD | | 600 million | VERMONT MOUNTAINS |
| PRE-CAMBRIAN | | | | ARIZONA MOUNTAINS<br>METALLIC ORE DEPOSITS<br>LAURENTIAN MOUNTAINS<br>ADIRONDACK MOUNTAINS |

*(Chart reprinted with permission of Hammond, Inc., Maplewood, N.J.)*

*The time spans above are listed for readers' convenience and apply to all articles in this issue.*

Some geologists, however, did apply Wegener's theory to their work. Emile Argand, working in the Alps, was among them. He postulated that Africa had pushed northward, shoving slabs of an ancient sea upon each other and over the European continent. Argand's work, like Wegener's and other "drifters," was regarded as unsubstantiated and preposterous by most of the geological community, and the theory of continental drift took a back seat to other geological interests.

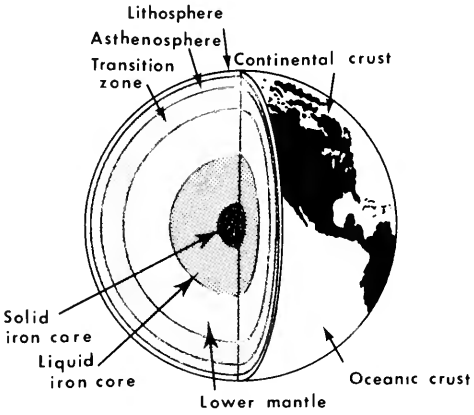
The evidence that would eventually convince geoscientists that large-scale horizontal motion had occurred over huge portions of the earth's crust was not available to Wegener and his contemporaries. That information lay beneath the 70 percent of the earth that is covered by oceans.

### Sea-Floor Spreading

It was not until after World War II that a major effort was mounted to understand more about the sea floor. Central to this effort was the mapping work of Bruce Heezen and Marie Tharp. They established the existence of a worldwide ridge and rift network on the ocean floor, a submarine mountain chain 65,000 kilometers long, extending into all oceans. Once located, these mountains were seen to follow a global zone of shallow earthquakes and high heat flow. This was where ocean crust was being created. Substantiation for the theory that ocean crust was being created at mid-oceanic ridges came primarily from two sources: magnetic patterns (see *Oceanus*, Vol. 17, No. 3), and sediments recovered by the drilling vessel *Glomar Challenger* (see *Oceanus*, Vol. 21, No. 3).

The earth has a magnetic field that affects certain metals. Many rocks contain magnetic minerals and when lavas are cooled or sediments are deposited, these magnetic minerals act like small magnets, pointing toward magnetic north. Throughout geological time, the earth's magnetic field has not been constant. It has varied in intensity and even experienced complete reversals in direction. These changes are worldwide and are recorded by the magnetic minerals in rocks. When these changes are correlated with other known geological events, the magnetic reversals can be dated. An independent time scale to determine the ages of the ocean was developed in this manner.

If ocean crust were in fact continually forming at and moving away from mid-oceanic ridges, magnetic anomaly patterns should be symmetrical on either side of the ridge. In 1965, the RV *Eltanin* ran a course perpendicular to the Pacific-Antarctic Ridge. When the magnetic patterns from that cruise were examined, they were found to be symmetrical about the center of the



ridge. With this information in hand, the available magnetic data were used to examine and date much of the ocean floor.

Some skeptics, however, were still not convinced. Ironically, though, it was the work of many people who initially rejected the plate tectonics theory that eventually helped to further prove the concept. Early in 1969, the *Glomar Challenger* drilled a series of holes across the South Atlantic ridge. These cores recovered sediments containing fossils that were progressively older as their distance from the ridge increased. The fossil ages were in remarkable agreement with the magnetic ages, lending more support to the theory that ocean crust in fact was being created at mid-oceanic ridges.

### What is Ocean Crust?

The dynamic processes involved in creating and moving ocean crust are not yet fully understood and are an exciting area of geological research. One of the first steps in this research is to determine the structure and composition of ocean crust. Like most scientific investigations, this problem may be approached from several directions. One is the study of ophiolites.

Ocean crust is hidden beneath thousands of meters of water. Bottom photographs and submersible observations are mostly limited to exploring the upper crustal surface. Yet, from measuring the speed at which sound travels through the ocean crust, we know that the composition changes with depth in a manner that suggests distinct and continuous layers. Three or four such crustal layers have been defined. All of these layers are exposed in ophiolites, which may be likened to geological rosetta stones. Before delving further into the nature of these layers, the basic geological processes involved in forming rocks need to be reviewed.

There are three major classifications of rocks: igneous, sedimentary, and metamorphic. Igneous (Latin for fire) rocks form from hot molten magma (greater than 1,000 degrees Celsius) that has cooled and solidified. Common examples are granites and basalts. Sedimentary rocks are formed by the consolidation of sediments. Sediments have several major sources: broken fragments of older rock, biological material, and remnants of evaporated saline environments. Deposited in rivers, oceans, deserts, and lakes, the loose sediments are gradually compacted and become lithified rocks. Specific types of sedimentary rocks are characteristic of different areas and particular environments. This information tells geologists where and how these rocks were formed. The biological component of the sediments, often preserved as fossils, tells not only what type of sedimentary environment — for example, ocean or river — but also the age of deposition.

When igneous or sedimentary rock is subjected to heat or pressure, it loses some of its initial characteristics and new minerals form. This is the metamorphic process. The types of new minerals that form indicate the amount of heat and pressure that the rock has experienced.

Igneous rocks are classified in several ways, but two major factors are taken into account: the chemical composition, usually reflected in the types of minerals that are present, and the size and shape of the mineral grains. It thus is possible for a rock with almost the same chemical composition to be called by a variety of different names. This is the case with ophiolites and ocean crust.

Chemically, the major subdivisions of magma and the rock types they form depend on the total percentage of silica ($SiO_2$) present, or on the percentage of light versus dark minerals. The two classifications are roughly equivalent. Rocks with the most silica-rich minerals are called felsic, and those with only silica-poor minerals, ultramafic. Between these two end members is an intermediate rock type called mafic, which is the composition of most ocean crust.

As magma cools, various minerals form at different temperatures. As they form, they remove material from the magma and alter the magma's composition. This enables ultramafic, mafic, and felsic rocks to form from the same magma.

Minerals take a long time to form, and, in a general way, their size reflects the amount of time that it took the rock to cool. Sometimes, magma cools so rapidly that very few minerals form, and the rock is actually a frozen liquid or glass. When mafic magmas cool rapidly, the rock that forms is basalt. When they cool slowly, gabbro (a course, crystalline rock) forms. Granite is a coarse, crystalline rock, but it has cooled from a magma richer in silica than gabbro. If the mafic magma cools in an amount of time intermediate between that of basalt and gabbro, disbase, a rock with small crystals, forms.

These three types of rocks — basalt, diabase, and gabbro — are the building blocks of the upper layers of an ophiolite and ocean crust. Basalt is found at the top, underlain by diabase and then by gabbro (Figure 3). The increasing crystal size reflects the increasing distance from the top of the ophiolite or ocean floor, and thus the longer cooling time.

The changes from one rock type to another are fairly abrupt. This abruptness and many unusual qualities concerning the shape and texture of ophiolite and ocean crust rocks reflect important information about their creation. Data are interpreted in many different ways, and the manner of ocean crust formation is currently the source of great controversy and speculation among the geological community. Nevertheless, a complex hypothesis has been proposed, which is meeting with varying degrees of consensus among geoscientists.

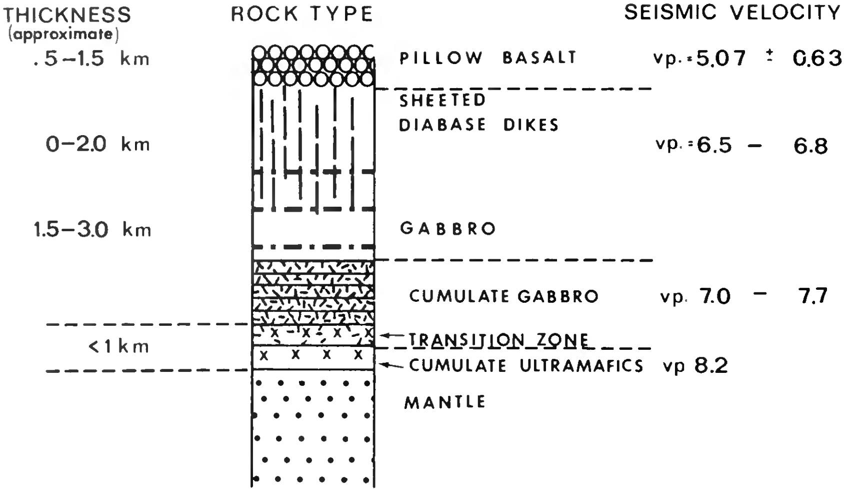


*Figure 3. An idealized cross section of an ophiolite or ocean floor. (Adapted from Peterson, and others,* Nature, *1974)*

Most hypotheses for creating ocean crust start with a magma chamber, where magma (from the Greek meaning paste) from the earth's interior collects. This magma chamber is probably located in or near the ocean crust. Some of the magma may bubble out of the chamber, forming undersea basalt volcanoes consisting of bulbous pillow shapes and glassy lava lakes (Figure 4). Forming a continuous layer under the basalt is a series of vertical sheets, termed dikes by geologists, that represent rapidly chilled crystalline magma. This magma was trapped in crustal fissures between other dikes as it moved from the magma chamber to the overlying sea floor. Some of these dikes extend hundreds of meters into the underlying gabbro layer.

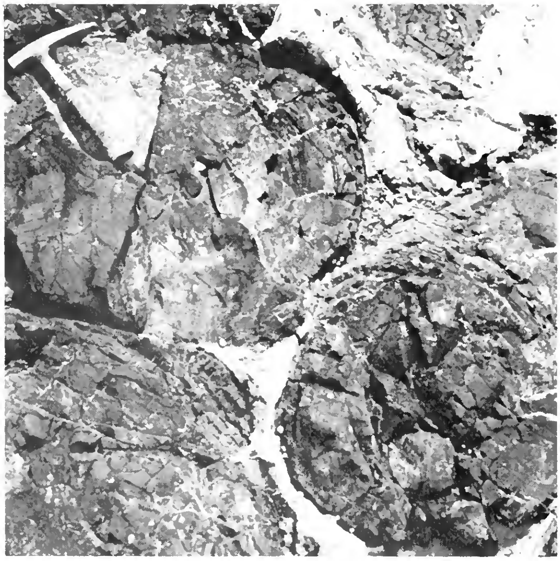


*Figure 4. Coastal exposure of pillow basalts in the Bay of Islands ophiolite complex in western Newfoundland (see Figure 8).*

As the edges and floor of the magma chamber slowly cool, coarse crystalline gabbro forms (Figure 5). The upper part of the gabbro consists of crystals that cooled directly against the side of the chamber. The lower gabbro is composed of crystals called cumulates that have accumulated on the magma chamber floor. As more is learned about the crystallization behavior of minerals in a magma, controversy is growing over the actual process by which cumulates form. Nevertheless, there is still a widely accepted hypothesis.

The cumulate crystals initially formed and grew in a liquid and therefore without constraints on the mineral boundaries. These minerals have an almost perfect crystal shape, like a single salt crystal growing on a string in saltwater. When the growing minerals become too heavy, they lose their buoyancy and sink. Depending on the composition of the mineral and the surrounding melt, and the rate of accumulation, different types of cumulate growth can occur. In one type of cumulate, the settled mineral continues to grow, impinging on neighboring minerals and losing its perfect shape. Some magma is caught in small pockets between the growing minerals and crystallizes, but most of the magma is squeezed out. In another type of cumulate, the settled minerals do not continue to grow. The magma surrounding them cools and crystallizes, and the settled minerals retain their perfect shape.

The most remarkable attribute of cumulate rocks is the presence of structures that resemble features usually observed in sedimentary environments (Figure 6). In sedimentary environments, these structures are created by changes in flow direction and in the ability of the water to carry sedimentary particles. The observation of these features in ophiolites suggests that the magma is moving. This could easily happen in response to temperature differences. The magma at the top and adjacent to the edges would cool and

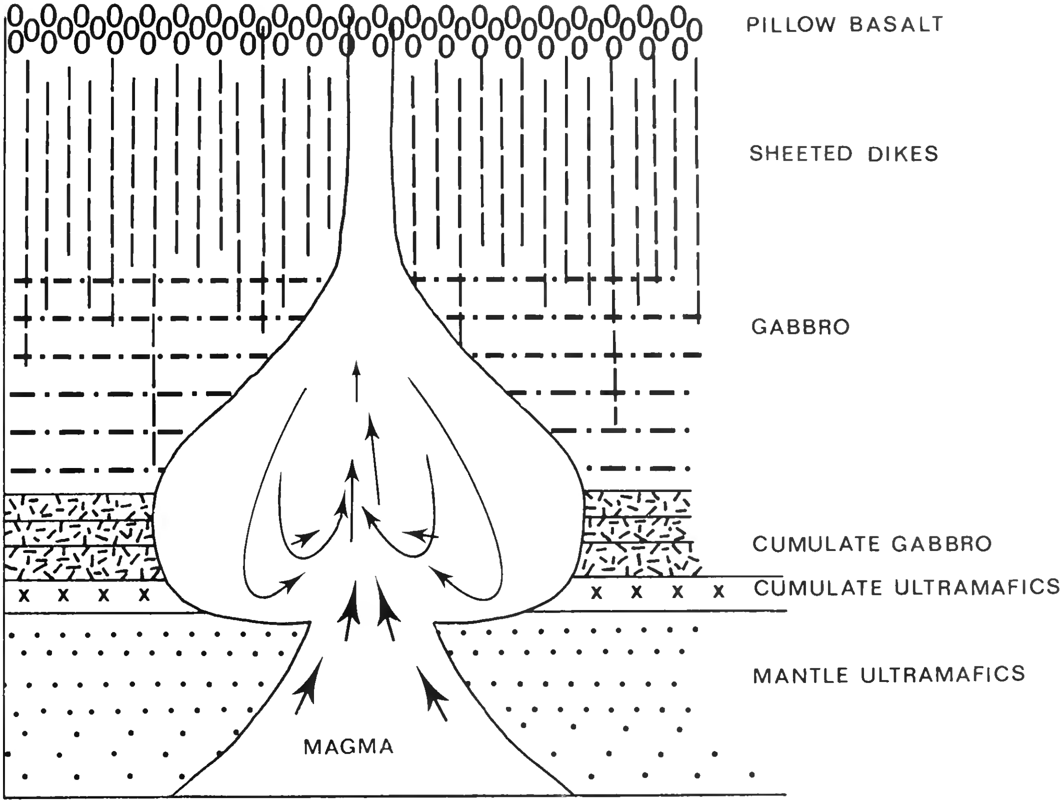


*Figure 5. Hypothetical magma chamber, showing material entering through the base with different crustal layers forming.*

sink, and the warmer material would rise, creating a circular movement known as convection.

Underneath the crust lies the mantle. This is a thick layer of the earth's interior between the crust and the core. Its occurrence below the crust is marked by an increase in the seismic velocity. This increase, first noted in 1909 by Andrija Mohorovičić at the University of Zagreb in what is now known as Yugoslavia, is frequently referred to as the Moho. Since ocean crust is thinner than continental crust, the mantle under the ocean is found at shallower depths. It consists of ultramafic rocks that have been partially melted, deformed, and recrystallized. Some of the melt that was removed from the mantle may have risen and have been incorporated into the material in the magma chamber. These mantle rocks are usually well exposed in ophiolites and form a thick basal sequence.

Between the mafic crust (basalt, diabase, and gabbro layers) and the ultramafic mantle lies a layer of ultramafic cumulate crust. The two types of ultramafics cannot be distinguished seismically. Yet they are usually seen in ophiolites. Like the cumulate gabbro, the cumulate ultramafics consist of crystals that settled out of the magma. The minerals that make up the ultramafics form at higher temperatures and are heavier than the minerals that make up the gabbro. This means that the peridotite* minerals crystallize earlier, and drop out of the magma more rapidly, collecting at the base of the magma chamber. The boundary between the two types of cumulates is often gradational, and a thick sequence of alternating layers of gabbro and peridotite develops (Figure 7).

Both types of ultramafics have undergone a process of low temperature alteration in which water becomes incorporated into the mineral structure. This process, serpentinization, produces a variety of shiny, dark green minerals called serpentinite. It is for this mineral that the entire ophiolite rock assemblage received its name. *Ophi* is Greek for serpent. Serpentinization obscures many of the original rock textures, making it difficult to distinguish the cumulate and non-cumulate rocks.

In an industrialized world with intensive resource utilization, there are important economic incentives to study ophiolites. Four different types of minerals have been mined from ophiolites: sulfide minerals (copper, zinc, and iron), chromite, laterites (iron and nickel), and talc/asbestos. These important minerals show considerable variation in abundance among different ophiolite complexes around the world. In some ophiolite complexes,

---

*A general term for essentially nonfeldspathic plutonic rocks consisting of olivine, with or without other mafic minerals. The other mafic minerals may be amphiboles, pyroxenes, and in some cases, micas.

*Figure 6. Details of cumulate gabbro layer. Linear bands indicate deposition in a quiet, stable environment. The cross-bedding in the lighter (more felsic) layers indicates a direction of transport (by convection currents) when the minerals were being deposited. The lighter layer was then partially eroded (along the light/dark boundary) and the darker (more mafic) layer was deposited.*

such as at Hare Bay in northwestern Newfoundland, no economically recoverable minerals have been found, whereas in others, such as at Troodos on Cyprus, there are extensive deposits.

Sulfide minerals occur as large deposits in the basalts. They form between pillow flows, at the basalt/sediment interface, and between the basalt and sheeted dike interface. Basalts associated with these deposits usually show evidence of extensive hydrothermal alteration. Recent dives on geothermal vents by the submersible *Alvin*, operated by the Woods Hole Oceanographic Institution, have recovered sulfide minerals with the basalt. Smaller amounts of sulfide minerals are sometimes found with the gabbros, but are not of sufficient quantity to be economically recoverable.

Archaeological evidence indicates that Cyprus was one of the first places, if not the first, to develop processes for smelting sulfide ores and mining copper. The Troodos ophiolite complex on Cyprus was a main source of copper for the Aegean and Near East throughout antiquity. Mining and smelting activities began about 4,000 B.C. and lapsed at the end of the 4th century A.D. after the decline of the Roman Empire. Mining was dormant until early in this century.

### Present Research

In April of this year, several hundred geoscientists from all over the world met in Cyprus to discuss and examine the current status of ophiolite research. Three major approaches are being pursued today: 1) detailed geological mapping of the ophiolite complexes, followed by petrological, geochemical, and geophysical studies; 2) comparing and contrasting ophiolite and ocean floor data; and 3) investigating the relationship of ophiolites to the surrounding rock.

Central to ophiolite studies are detailed geological maps. Most of the existing maps are general. As mentioned previously, we know the major ophiolite components. Now geologists are trying to determine the relationship of the major components to each other, and to the smaller-scale internal features. Recent work (in which the author is involved) on the four massifs of the Bay of Islands ophiolite complex in Newfoundland (Figure 8) shows that the internal orientation of the gabbro layers is variable, and does not parallel the major boundaries. This has important implications for the formation of ocean crust, particularly the shape and behavior of the magma chamber.

Once detailed structural relationships have been determined and geological maps have been

*Figure 7. Thick layers in the mafic/ultramafic transition zone near the crust/mantle boundary.*

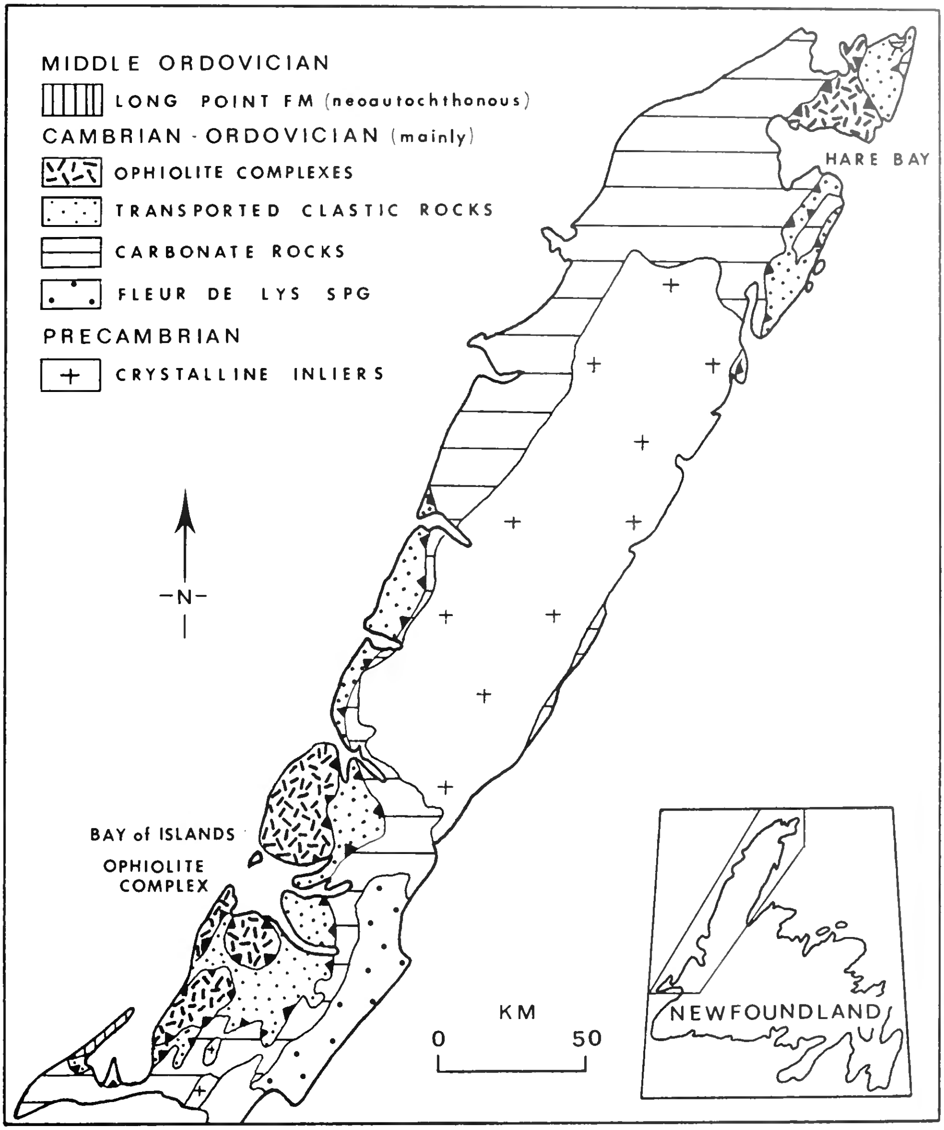


*Figure 8. Western Newfoundland, showing the location of the Bay of Islands and Hare Bay ophiolite complexes. (From H. Williams, 1975. Reproduced by permission of the National Research Council of Canada)*

made, chemical, velocity, and magnetic analyses are performed on the samples. These analyses help to show the development and evolution of the ophiolite, and, equally important, the results from these studies are compared with similar studies of ocean floor samples. Since ocean floor cannot be sampled with the same structural precision as ophiolites, this comparison is advantageous in interpreting the structure of both ocean crust and ophiolites and how they are formed.

From this work, a new approach to interpreting ocean crust is emerging. Although it is certainly not as complex as continental crust, ocean crust is considerably more complex than had been imagined five years ago. In part, this may reflect the complexities of the areas being sampled. Submersibles are limited to fracture zones and steep fault scarps when sampling the deeper crustal layers. Ophiolites, by their very location, have undergone an intense period of rupturing and uplift that complicates their history. Further, it is not clear in which part of the ocean floor ophiolites originated. Do they represent marginal basins, fracture zones, initial rifting of continental crust, or island arcs? Ophiolites probably formed in all of these environments, and their variability reflects both their diverse origins and their emplacement history.

The emplacement history is the third major line of research. This involves stepping beyond the ophiolite proper into the surrounding rock types. How do the fossil ages in the surrounding rock compare with the radiometric ages of the ophiolite? Are the surrounding rocks likely to have been formed in deep or in shallow water? What is the nature of the contact between the ophiolite and the underlying rock?

Using the large-scale features of geosutures, geoscientists are able to locate oceans that have disappeared. This was eloquently done in 1966 by J. Tuzo Wilson of the University of Toronto in his prediction that the Appalachian-Caledonian mountain range, extending from Alabama across the North Atlantic to the British Isles and Norway, was the site of a proto-Atlantic ocean (Figure 9). This ocean closed about 400 million years ago. The small-scale features and mineral composition at the contact between the ophiolite and surrounding rocks are used to describe how the emplacement occurred.

During the last two years, the DV *Glomar Challenger* has drilled into several circum-Pacific subduction zones, repeatedly failing to recover information supporting the present hypothesis of subduction. Since the plate tectonic theory holds that ophiolites are one of the end products of subduction, the relationship between ophiolites, associated sediments, and the surrounding rocks is being studied with renewed intensity.

At their base, many ophiolites and surrounding rocks show evidence of elevated temperatures. Looking at details of the minerals at the base of the Hare Bay ophiolite complex, Rebecca Jamieson of Memorial University in Newfoundland has proposed a model suggesting that the elevated temperature involves both conduction and frictional heating of surrounding rocks as the ophiolite is thrust over them. This model describes what may be a normal process accompanying ophiolite emplacement and continental growth.

The finer-scale processes of the plate tectonic puzzle are far from being solved. Ophiolites will continue to hold important information about three of the major areas of current geological research — ocean crust formation, subduction processes, and continental growth. These ancient slabs of oceanic crust — utilized more than 6,000 years ago by the Cypriots and puzzled over by geologists for centuries — continue to yield important mineral and scientific wealth.

*Suzanne O'Connell is Science Coordinator in the office of the Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES) at the Woods Hole Oceanographic Institution.*

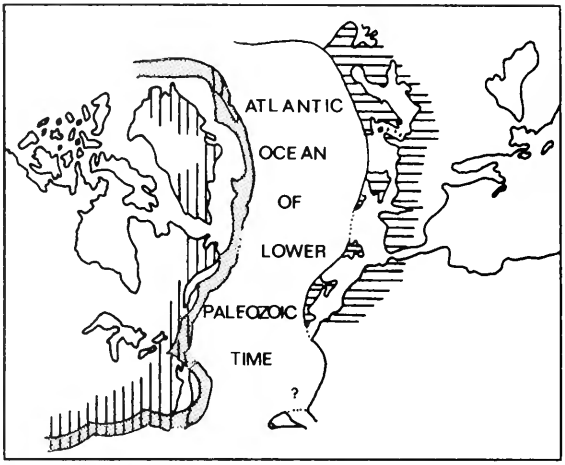


*Figure 9. Geosuture, showing location of proto-Atlantic ocean, which disappeared 400 million years ago. (From Wilson,* Nature, *1966)*

**References**

Casey, J., J. Karson, S. O'Connell, and E. Rosencrantz. *In press.* Comment on "The seismic velocity structure of a traverse through the Bay of Islands ophiolite complex, Newfoundland, an exposure of oceanic crust and upper mantle," by M. H. Salisbury and N. I. Christensen. *Journal of Geophys. Res.*

Coleman, R. D. 1977. *Ophiolites.* Berlin-Heidelberg, Germany: Springer-Verlag.

Heirtzler, J. R. 1969. Sea-floor spreading. *Sci. Am.* 219 (4): 60-70.

Jamieson, R. A. 1979. The origin of the dynamothermal aureole beneath the White Hills peridotite and its bearing on ophiolite emplacement. Geological Association of Canada, Mineralogical Association of Canada, *Annual Review* 4: 60.

Maxwell, A., R. Von Herzen, et al. 1969. JOIDES Deep Sea Drilling Project, Leg 3 and Leg 4. *Geotimes* 14(6): 13-16.

Pitman, W., and J. R. Heirtzler. 1966. Magnetic anomalies over the Pacific-Antarctic ridge. *Science* 154(3753): 1164-71.

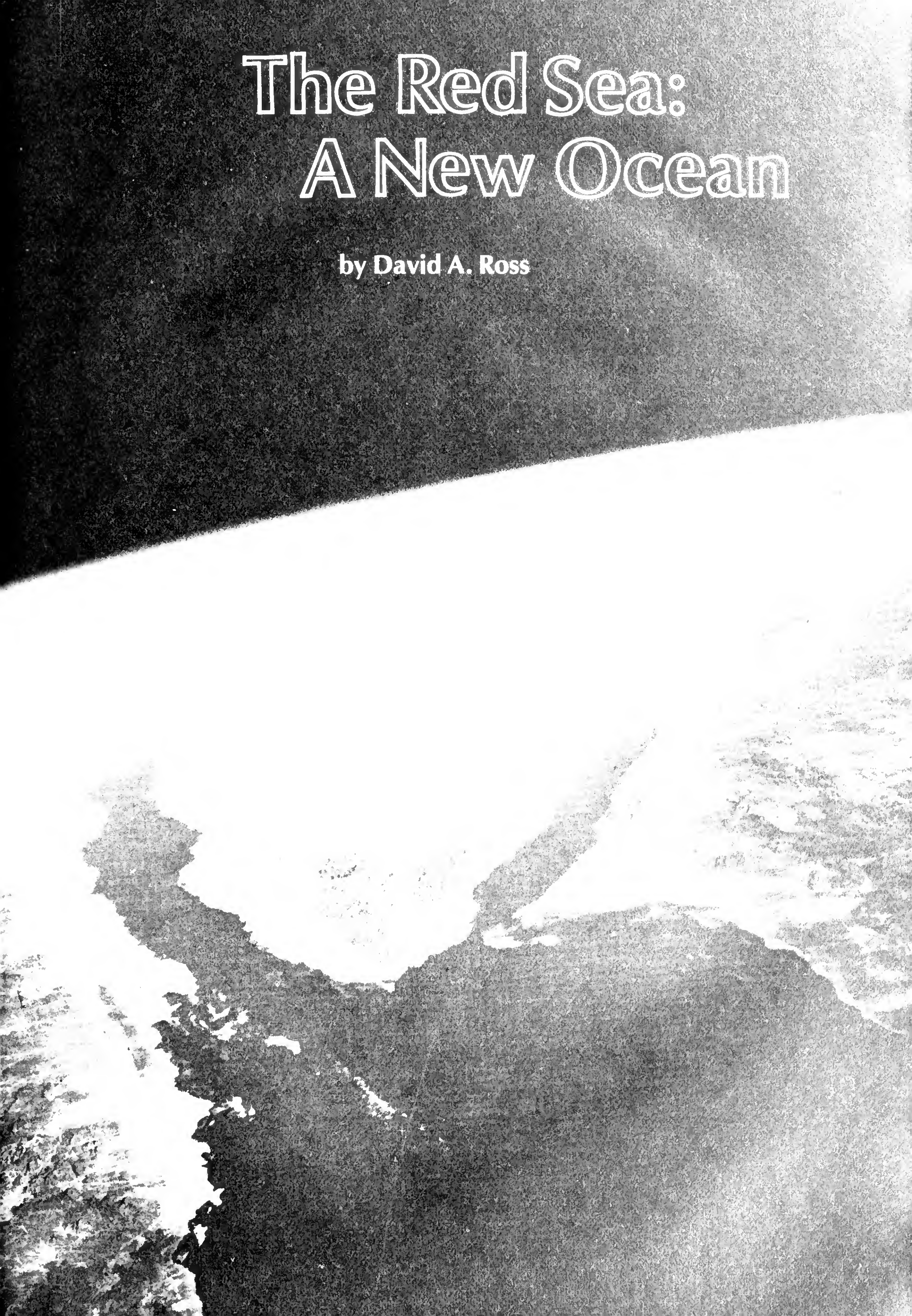
Vine, F., and D. Matthews. 1963. Magnetic anomalies over oceanic ridges. *Nature* 199(4897): 947-49.

Williams, H. 1975. Structural succession, nomenclature, and interpretation of transported rocks in western Newfoundland. *Can. Jour. Earth Sci.* 12: 1874-94.

Wilson, J. T. 1966. Did the Atlantic close and then re-open? *Nature* 211: 676-81.

# The Red Sea: A New Ocean

by David A. Ross



The concept of sea-floor spreading and plate tectonics allows marine scientists to predict the future shape of an ocean basin and to deduce its past configuration. It is generally accepted, for example, that the Atlantic Ocean started opening about 200 million years ago, initially when South America separated from Africa, and later when North America and Europe came apart. The breakup probably started with a broad upwelling of the crust, followed by thinning, and then gradual splitting or rifting apart. The two new continents then continued spreading apart with new ocean crust forming by volcanic activity in the resulting central rift. In the early stages of the split, the new sea was long and narrow, probably with isolated depressions. Its connection with the ocean was restricted, and evaporitic conditions often developed, which led to extensive salt deposits. Kevin Burke of the State University of New York at Albany has detected such ancient deposits buried below parts of the continental margin surrounding the Atlantic Ocean; areas that represent the oldest sections of the original Atlantic Ocean.

Thus an interesting question is: Do we have a modern analog of an ocean basin in its early stages of formation? The Red Sea, at present, appears to be such a region — it is slowly opening as the Saudi Arabian Peninsula and Africa are moving away from each other.

To appreciate sea-floor spreading in the Red Sea, it is valuable to look at the entire Arabian Plate (Figure 1). As the Red Sea is slowly opening to the northeast at a rate of 1 or so centimeters a year, it causes a slow compression of the Persian Gulf against the Asian continent, thrusting (subducting) it and the coastal area of Iran under the adjacent continental region. This region is called the Zagros Thrust Zone; the Zagros Mountains have been formed by this compression. At the rate at which the Red Sea is opening, it will take about 25 million years for the Persian Gulf to be completely subducted, and for Saudi Arabia and Iran to actually collide. Such a continent-to-continent collision appears to be already occurring in parts of the Gulf of Oman. Translation movements, where plate boundaries slide by parallel to each other, occur in the Gulf of Aqaba (Elat), the Dead Sea, and the Jordan Rift Valley up to northern Syria (the entire length of this feature is often called the Levant Fracture Zone). A similar type of motion also occurs in the Indian Ocean along the Owen Fracture Zone and the Oman Line, which offsets the subduction along the Zagros Thrust Zone and Gulf of Oman.

Seismic profiles from the Red Sea show that the entire region, except its central rift, is underlain by a strong acoustic reflector called S (Figure 2). The *Glomar Challenger* — the ship specially built for the Deep Sea Drilling Project which evolved into the multi-nation International Program of Ocean Drilling — has drilled into this reflector in several localities, and scientists have found it to be the top of a thick evaporitic sequence whose deposition terminated at the end of the Miocene (about 5 million years ago). In some areas, the deposit is almost 3 kilometers thick, indicating that it formed over an extensive period of time. The reason for the absence of the reflector (and therefore the evaporite) from the central rift is because this part of the rift was not present 5 million years ago, but has developed subsequently by spreading. Thus if we were to match up both sides of the sea floor (excluding the rift) and align it with reflector S, we would see the configuration of the Red Sea prior to the most recent rifting.

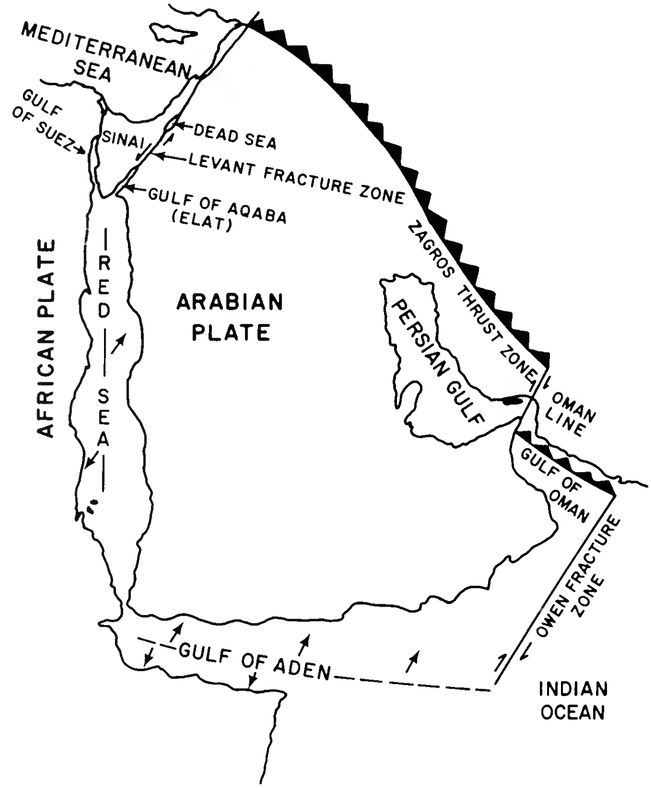


*Figure 1. Major features of the Arabian Plate. Sea-floor spreading is indicated by full arrows, translation by half arrows, and subduction by the wedged zone.*

**OVERLEAF**
*Apollo 7 view of the Red Sea, foreground, showing the gulfs of Suez and Aqaba. The eastern end of the Mediterranean is below the clouds on the horizon. (Photo courtesy NASA)*

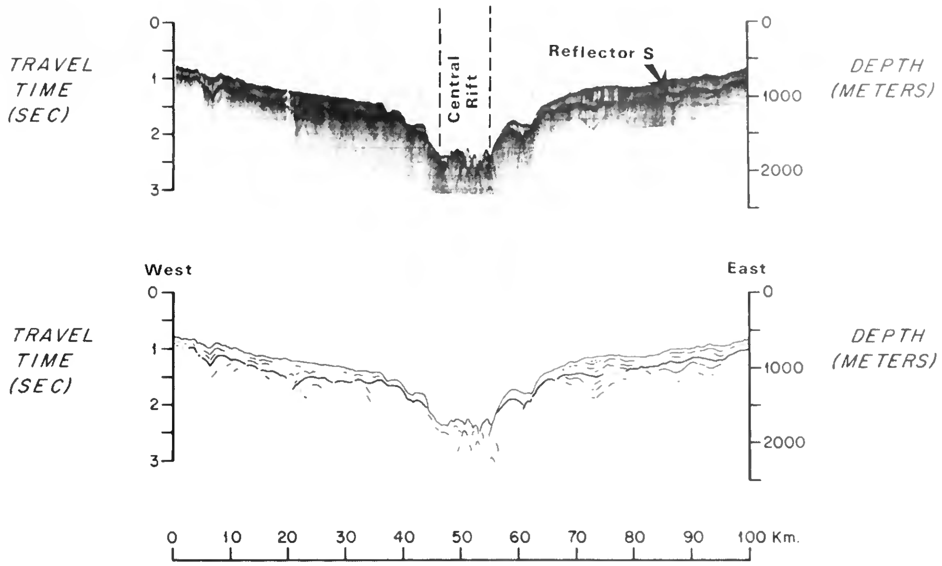


*Figure 2. Seismic profiles (original, upper; and interpretation, lower) made across the Red Sea. Note the absence of sedimentary material in the central rift, and the presence of reflector S underlying all of the region, except the central rift.*

A seismic profile from the Persian Gulf shows the plunging or dipping of acoustic reflectors under the continental area of Iran (Figure 3). Another expression of the collision of the Persian Gulf with Iran that has resulted from the opening of the Red Sea is large-scale folds caused by the compression. Several important offshore oil fields are the result of structural traps formed by this folding.

Even though the present Red Sea appears to be an excellent example of sea-floor spreading in its early stages, there is still considerable controversy about its origin. The debate, nicely summarized by Xavier LePichon and Jean Francheteau of the Centre National pour l'Exploration des Océans, is over how much of the Red Sea's present width is due to sea-floor spreading, and how much is a result of thinning and stretching of the continental crust preceding and during early spreading. The argument is important because it bears on the origin of continental margins in general — do they form in the early stages of spreading as a result of crustal thinning, or, when continents break apart, do they do so in a rigid manner that results in a sharp break between the continental crust and the new oceanic crust with the continental margin developing later?

There are good arguments on both sides of the debate. D. P. McKenzie of the University of Cambridge and his colleagues contend that the adjacent Red Sea coastlines fit nicely together and therefore that the entire present Red Sea must be underlain by oceanic crust. This point is weakened, however, because the present coastline does not represent a unique border (just the present position of sea level) and indeed other researchers, such as R. W. Girdler and B. W. Darracott, and R. Freund, have fitted, equally successfully, lines as far as 50 kilometers offshore. Magnetic anomaly patterns,* usually the ultimate evidence in sea-floor spreading controversies, are somewhat contradictory in their expression. Magnetic anomalies are evident and easily interpreted in the central rift, and most experts agree that this part of the Red Sea was formed by recent sea-floor spreading and is underlain by volcanic rock. This spreading, however, only covers a period of about 3 to 4 million years. Closer to shore, magnetic anomalies are not very clear or easily interpreted, although researchers claim to have found some that may be as old as 34 to 41 million years. The evidence, in my opinion, although interesting, is not definitive. It comes from a very small region of the Red Sea. One would think, for example, that magnetic spreading anomalies would be more evident and parallel most, if not all, of the central valley of the present Red Sea, if it had been formed by spreading. Others argue that much of the width of the present Red Sea is the result of continental thinning, but they do not have unequivocal evidence either. Everyone agrees that spreading presently is occurring along the central rift, and has been doing so for the last few million years. Perhaps in the future either drilling or

---

*Positive and negative magnetic anomalies that often symmetrically parallel a ridge or other feature if it was formed by sea-floor spreading.

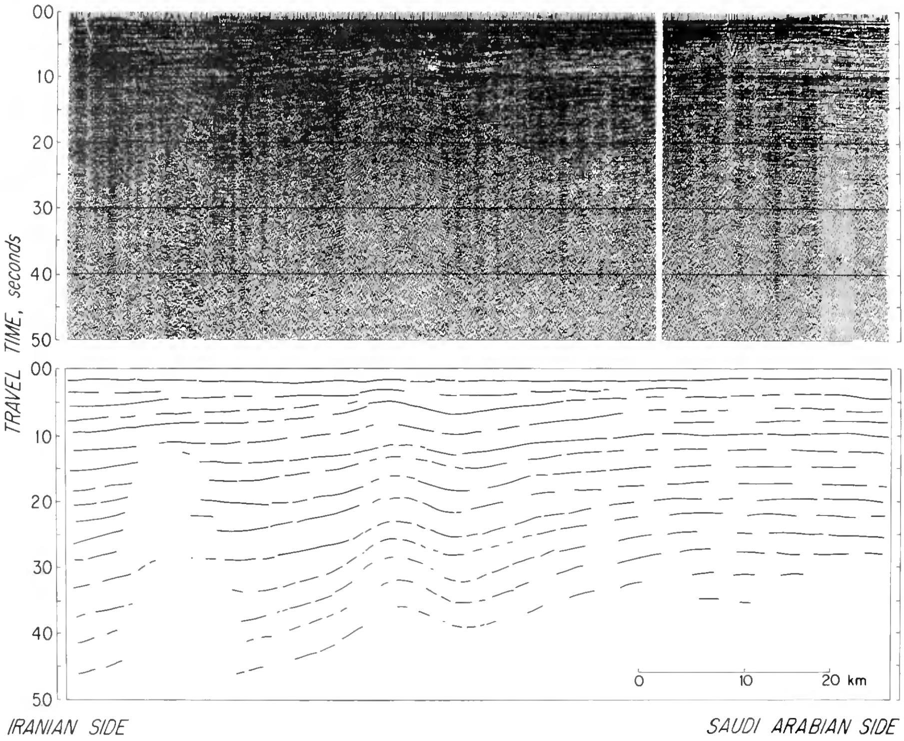


*Figure 3. Seismic profile made across the Persian Gulf (original, upper; and interpretation, lower). Note the thickening of the sedimentary section toward the Iranian side.*

multi-channel seismic work* can define what type of crustal rock is underlying the Red Sea, and, in so doing, tell us much about the origin of continental margins in general.

### Hot Brine Areas

A discussion of the Red Sea would not be complete without describing its so-called hot brine areas (Figure 4). More than a decade ago, a series of pools or deeps containing hot, salty water were discovered along the bottom of the central rift (see *Oceanus,* Vol. 13, Nos. 2 and 3, 1967). Over the years, they have been extensively studied by American, German, British, and Soviet oceanographers, and by 1969 more than 100 papers had been written on the three main ones — the Discovery, Atlantis II, and Chain Deeps (named after the ships that participated in their discovery). Often underlying these pools are sediments highly enriched in various heavy metals. In more recent years, a series of expeditions by the West German vessel *Valdivia* found 13 new pools along or adjacent to the central rift valley. At present, the Atlantis II Deep is the best known and most valuable economically. In general, the pools result from hot, very salty (therefore dense) water being discharged onto the sea floor; if it enters into a closed depression, the water can accumulate, forming a pool. The process is similar to the hot water vents on the central rift of the East Pacific Rise near the Galápagos Islands and off Mexico (see *Oceanus,* Vol. 22, No. 2). The key difference is that the Red Sea water is denser than seawater and thus accumulates along the bottom, whereas in the Pacific the water dissipates when mixed because it is less dense than normal seawater. Apparently the salt horizons of the Red Sea (evaporites underlying reflector S) may contribute to the high density of the discharged water. This can occur when migrating fluids transform these rocks into a solution. The actual process of the discharge, on the other hand, may be quite similar to that occurring on the East Pacific Rise and off Mexico near the Gulf of California. The latter region is thought by many to also be an ocean basin in its early stages of formation.

Numerous expeditions to the Red Sea hot brine area have clearly documented the hydrothermal nature of the region and the increasing temperature of the bottom-lying brines. The highest water "salinity" — about 257 parts per thousand (or about seven times normal seawater) — has been recorded in the Atlantis II Deep. However, the ratio of the major ions in the brines is not similar to seawater, thus it is not salinity in oceanographic

---

*Multi-channel seismics, besides obtaining seismic velocities, generally allow deep penetration (4 or 5 kilometers or more) of the ocean floor. These two aspects may be used to determine whether the underlying crustal rock is continental or oceanic.

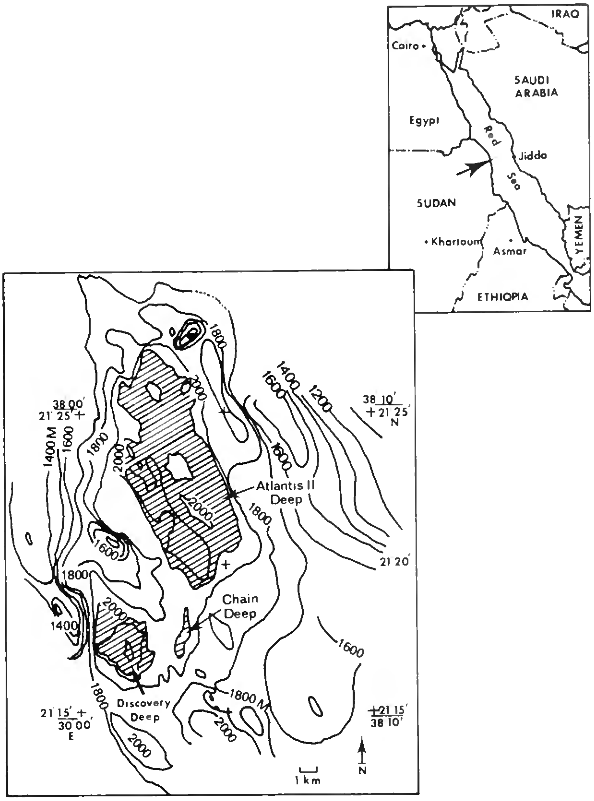


*Figure 4. Bathymetric chart of the Atlantis II hot brine region of the Red Sea.*

terms. The keen interest in the area lies in the fact that the sediments underlying the brines are significantly enriched in heavy metals, such as copper, zinc, lead, and silver. The in situ value of the sediments in the Atlantis II Deep has been estimated to be in the billions of dollars.

One of the most important scientific aspects of the region is its present activity, evidence of which can be found in increasing water temperatures. The Atlantis II Deep water, which seems to be the source area for the waters in the Discovery and Chain Deeps, increased in temperature during the 1965-1971 period. Waters from the Atlantis II Deep can be divided into a hotter, lower layer (I), and a relatively cooler, upper layer (II), separated by a zone of rapid temperature change (Table 1 and Figure 5). Overlying the upper layer is a transition zone (III), where the brines and the Red Sea waters are mixed together. Scientists at the Woods Hole Oceanographic Institution and elsewhere have shown that the increase in temperature in the lower layer (I) from 1966 to 1971 (56.5 to 59.2 degrees Celsius) was 2.7 degrees Celsius in 52 months, or 0.052 degrees Celsius per month. During this period, the height of the lower water (I) rose about 7 meters. This calculated to an input of 0.346 cubic kilometers of water during this time period. The upper brine (II) increased in temperature from 44.3 to 49.7 degrees Celsius. The height of the transition zone (III) also increased by 7 meters. Calculations for the change in the 1966-1971 period show that the minimum temperature of the new incoming brine is about 104 degrees Celsius, and that the rate of input is about 2.6 cubic meters per second, or 700 gallons per second; a rate about 200 times greater than Old Faithful Geyser in Yellowstone National Park.

In April 1977, I returned to the Atlantis II region (my fourth trip there in 11 years), anticipating a continuation of the past temperature trends. Our observations, however, indicated an interesting change in the Red Sea brine system. The lower layer (I) had a temperature of 61.3 degrees (Table 1); however, a temperature of about 64 degrees Celsius should have been observed if the rate of temperature increase continued. The observed temperature increase of only 2.1 degrees Celsius over 97 months is 0.021 degrees Celsius per month, or less than half the past rate. The temperature of only 61.3 degrees Celsius was also surprising in light of the measurements from *Valdivia* in February-March 1972, which showed an increase at that time to as high as 60.8 degrees Celsius in the April, 1971, to March, 1972, interval. Even more surprising is that the temperature of the upper layer (II) has dropped from 49.7 to 49.45 degrees Celsius. The increase in the height of the lower water (I) was 25 meters (in 97 months) compared to 7 meters (in 52 months for the 1966-1971 interval). The transition water rose 28 meters compared to 7 meters. These

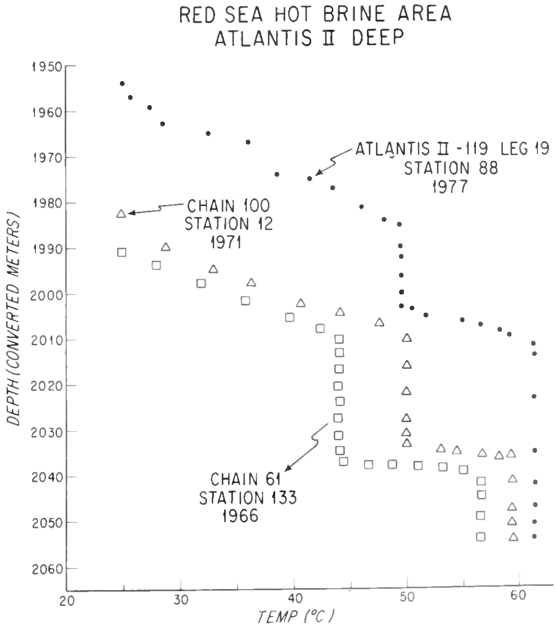


*Figure 5. A series of temperature profiles made in the Atlantis II Deep. All the measurements were made with the same device – a temperature telemetry pinger.*

**Table 1. Summary of Red Sea brine measurements from Atlantis II Deep.**

| Layer | | 1966 | 1971 | 1977 |
|---|---|---|---|---|
| III | Top of transition zone (m) | 1,989 | 1,982 | 1,954 |
| II | Temperature of upper layer (C°) | 44.3 | 49.7 | 49.45 |
| | Depth of upper layer (m) | 2,010 | 2,009 | 1,985 |
| | Bottom of upper layer (m) | 2,037 | 2,033 | 2,003 |
| I | Temperature of lower layer (C°) | 56.5 | 59.2 | 61.3 |
| | Depth of lower layer (m) | 2,042 | 2,035 | 2,010 |

observations clearly point to an increased input of water. Using the previous series of calculations, the 1977 data indicate an average input temperature (temperature of the new, incoming waters) of only 69 degrees Celsius (compared to about 104 degrees Celsius before). Considering the volume, the new increase is about 1.23 cubic kilometers, or about twice the past rate. It thus appears that although the rate of input of new water has increased, its temperature has decreased. It also seems reasonable that the waters of the Atlantis II Deep have overflowed their sill and are presently discharging hot brine into other parts of the Red Sea — a condition that has occurred several times in the past (explaining the presence of brine in the adjacent Discovery and Chain Deeps).

The best map of the brine region, compiled by German scientists, shows that a sill at a depth of about 2,000 meters exists between the Atlantis II Deep and the Chain and Discovery Deeps. Because of the unknowns of sound velocity in such hot and salty water, however, the true depths cannot be calculated, and differences of 5 or 10 meters are possible. Thus it may be that Atlantis II Deep brines are presently overflowing their sill and spreading out into the Chain and Discovery Deeps, and perhaps elsewhere. Measurements in the coming years, both in the Atlantis II region and elsewhere, should indicate whether Atlantis II water is indeed spreading into other deeps.

The second interesting aspect of the Red Sea brine area is its economic value. The economic potential of the sediments underlying the brines was appreciated very early in the exploration of the region, and, as previously stated, estimates placed the value of the top 10 meters of the Atlantis II Deep in the billions of dollars. This deposit lies almost equidistant between Saudi Arabia and Sudan, and these two countries have formed a Joint Red Sea Commission for the purposes of exploration and exploitation of these sediments. The Commission has contracted with Preussag AG, a large West German mining company, to explore the region, and, using *Valdivia,* they have been responsible for many of the previously mentioned discoveries. Although scientists from this organization have

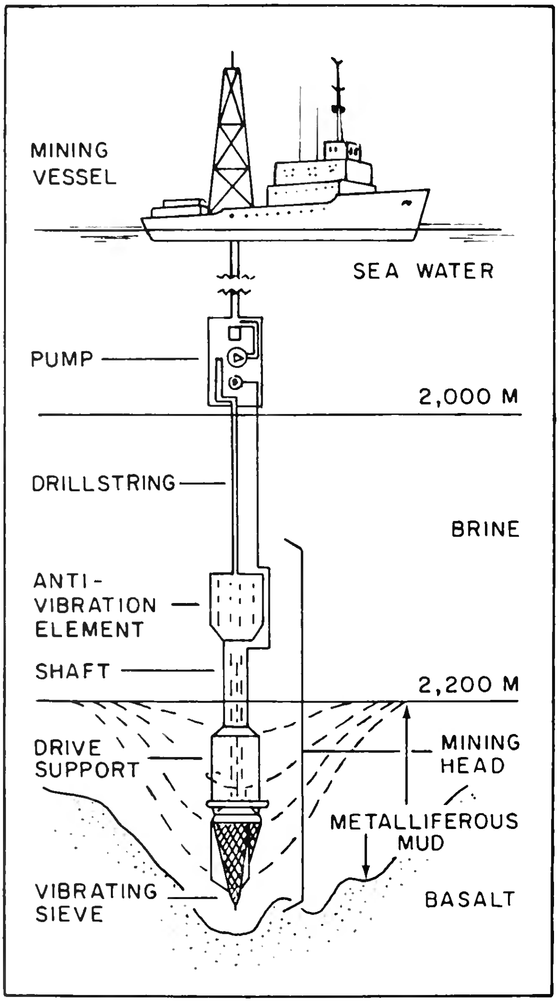


*Figure 6. Red Sea mining system developed by Preussag AG and O&K Orenstein and Koppel (adapted from* Ocean Industry, *May, 1979).*

published a considerable amount of data on their research, it has been a matter of speculation when (and perhaps if) these deposits would be mined. Recent trade magazine articles indicate that work may begin soon. Preussag AG with O&K Orenstein and Koppel Aktiengesellschaft, another West German company, recently tested a system that could be used to recover the sediments from the Atlantis II Deep (Figure 6). These sediments have a relatively high water content, which would make it easy to mine them if they were in shallow water. However, their presence at more than 2,000 meters, combined with variations in lithology (some basalt layers are possible), may make mining difficult. The German companies have devised new technology to lift the sediments from the sea floor. Their system uses a drill string with a head containing a vibrating sieve and three high-pressure water jets. When it is in place, the sediment is loosened by the vibration of the sieve and the water jets. The "fluidized" sediment is then sucked up through the sieve to the surface ship. This system has already been successfully tested in several shallow-water environments, and production from the Red Sea is expected to begin by 1985. The plan is to mine about 100 to 150 thousand tons of mud per year for 15 to 20 years.

It now appears that the Red Sea heavy-metal deposit may be the first one to be mined from the deep sea — even before the much heralded manganese nodules. One should emphasize, however, that few if any legal problems affect the Red Sea heavy-metal deposits because they lie in a narrow sea surrounded by land, ownership belonging to Sudan and Saudi Arabia. This fact is a direct result of the early age of the Red Sea in its sea-floor spreading evolution.

*David A. Ross is an Associate Scientist in the Department of Geology and Geophysics at the Woods Hole Oceanographic Institution.*

## References

Backer, H. 1975. Exploration of the Red Sea and Gulf of Aden during the *M.S. Valdivia* cruises. Erzschlamme A and Erzschlamme B. *Geologisches Jahrbuch* D-13: 3-78.

Backer, H., and M. Schoell. 1974. New deeps with brines and metalliferous sediments in the Red Sea. *Nature* 240: 153-58.

Brewer, P. G., T. R. S. Wilson, J. W. Murray, R. G. Nunns, and D. C. Densmore. 1971. Hydrographic observations on the Red Sea brines indicate a marked increase in temperature. *Nature* 231: 37-38.

Coleman, R. G. 1974. Geological background of the Red Sea. In *The geology of continental margins*, ed. by C. A. Burk and C. L. Drake. New York, N.Y.: Springer-Verlag.

Degons, E. T., and D. A. Ross, eds. 1969. *Hot brines and recent heavy metal deposits in the Red Sea*. New York, N.Y.: Springer-Verlag.

Freund, R. 1970. Plate tectonics of the Red Sea and East Africa. *Nature* 228: 453.

Girdler, R. W., and B. W. Darracott. 1972. African poles of rotation. *Comments Earth Science Geophys.* 2: 131-38.

Girdler, R. W., and P. Styles. 1974. Two-stage Red Sea floor spreading. *Nature* 247: 1-11.

Hahlbrock, V. 1979. Mining metalliferous mud in the Red Sea. *Ocean Industry* May: 45-48.

LePichon, X. and, J. Francheteau. 1978. A plate-tectonic analysis of the Red Sea-Gulf of Aden area. *Tectonophysics* 46: 369-406.

Lowell, J. D., and G. J. Genik. 1972. Sea-floor spreading and structural evolution of southern Red Sea. *Amer. Assoc. Pet. Geol. Bull.* 56: 247-59.

McKenzie, D. P., D. Davies, and P. Molnar. 1970. Plate tectonics of the Red Sea and East Africa. *Nature* 226: 243-48.

Roeser, H. A. 1975. A detailed magnetic survey of the southern Red Sea. *Geologisches Jahrbuch* D 13: 131-53.

Ross, D. A. 1972. Red Sea hot brine area: revisited. *Science* 175: 1455-57.

Ross, D. A., and J. Schlee. 1973. Shallow structure and geologic development of the southern Red Sea. *Bull. Geol. Soc. Amer.*, 84: 3287-3848.

Schoell, M. 1976. Heating and convection within the Atlantis II Deep geothermal system of the Red Sea. Proceedings 2nd U.M. Symposium on the development and use of geothermal resources, 1: 583-5901.

Schoell, M., and M. Hartmann. 1973. Detailed temperature structure of the hot brines in the Atlantis II Deep (Red Sea). *Marine Geology* 14: 1-14.

Stoneley, R. 1974. Evolution of the continental margins bounding a former southern Tethys. In *The geology of continental margins*, ed. by C. A. Burk and C. L. Drake. New York, N.Y.: Springer-Verlag.

White, R. S., and D. A. Ross. 1979. Tectonics of the western Gulf of Oman. *Jour. Geophy. Res.*, Vol. 84, No. B7: 3479-89.

# The Continental Margins

### by John S. Schlee, David W. Folger, William P. Dillon, Kim D. Klitgord, and John A. Grow

In a world concerned with evaluating future energy sources, study of the continental margin off the Atlantic coast takes on special significance. Do the Atlantic continental margins — areas of large sediment accumulations — possess the potential for large petroleum resources? Exploration to determine whether reservoir rocks and traps are present is currently underway, on both sides of the Atlantic. But continental margins also are important because they give scientists clues as to how continents form and because they represent the "growing edge" of the land mass. The processes creating modern margins allow us to interpret earlier phases of the earth's history, which can be seen in the folded, uplifted rock of inland mountain ranges.

In general, continental margins are thought of as either Atlantic (passive) or Pacific (active) types. If the margin is of Atlantic type, the continent has subsided along its edge so that older continental crust is buried by a prism of younger sediment: Pacific-type margins have a folded-faulted edge, reflecting the pushing of the crustal edge over oceanic crust. The two types of continental margins originate as part of the same general evolutionary process — sea-floor spreading. In this process, new oceanic crust is created at the mid-oceanic ridges, as the continents along with adjacent sea floor move away from each other. The hypothesis implies that the continents bordering the Atlantic were touching at one time, and split apart as the present ocean basins were formed. Continental margins facing the newly forming Atlantic Ocean gently subsided following continental separation. At the western edge of the Americas facing the Pacific, the continents have over-ridden oceanic crust to give rise to an active margin marked by uplift as mountain ranges (the Andes), volcanism, and earthquakes.

The continental margin off the Atlantic coast is one of the most extensively studied areas of the world. Sediments in this area were first sampled and mapped in the 19th century by L. F. Pourtales, and some of the earliest marine geophysical surveys were made off the mid-Atlantic states in the late 1930s by Maurice Ewing and his colleagues. As more knowledge of this margin and others was gained, it could be seen that the Atlantic margin was similar in shape to others.

The margins of the world are composed of three *depth* zones — shelf, slope, and rise. The shelf area, which may vary from 30 to more than 300 kilometers in width, is a relatively shallow zone, extending from the coastline to slightly less than 200 meters in depth. The slope is narrow, extending from a point known as the shelf break, where the sea floor drops rapidly from less than 200 meters to 3,000 to 4,000 meters. The base of the slope is usually defined as that point where the sea-floor gradient drops below 1 in 40, producing a more gentle, seaward-sloping continental rise, extending

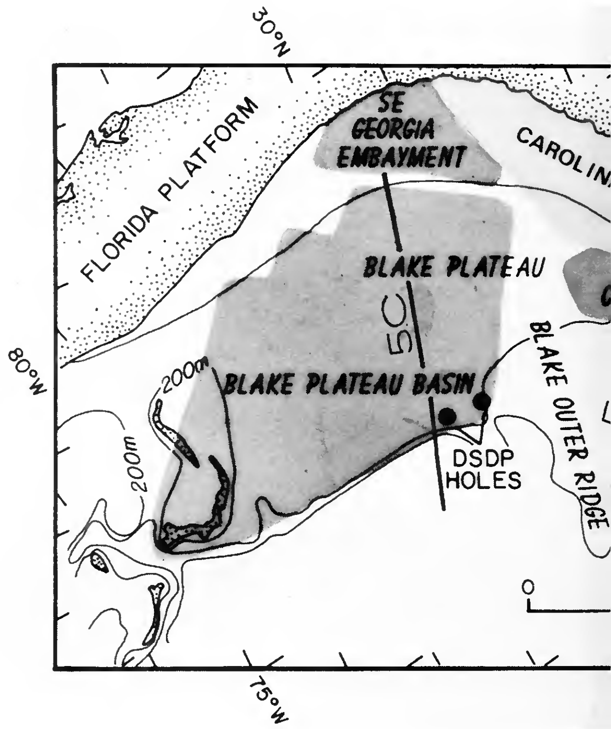


*Figure 1. U.S. Atlantic continental margin, showing location of major sediment-filled basins and platforms. Labeled are the locations of the cross sections shown in Figure 5.*

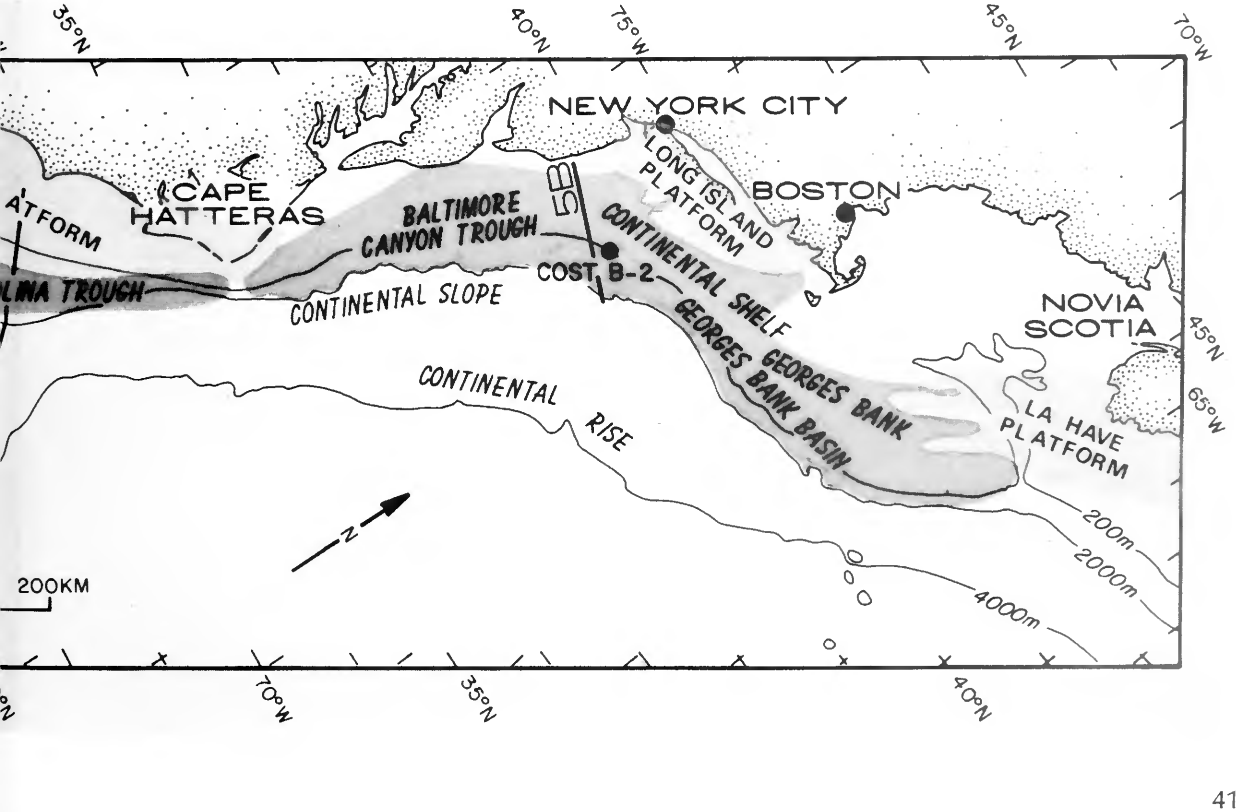
# of the Western North Atlantic

from a depth of 4,000 to 6,000 meters. The rise can range from 80 to more than 500 kilometers in width, giving way at the margin boundary to an abyssal plain.

For the margins bordering the North Atlantic, the shelf, slope, and rise are underlain by a sediment layer that, in places, reaches a thickness of 17 kilometers. Beneath the sedimentary accumulations on the margin lies a more complex structural foundation of igneous and metamorphic rocks, which was there when the margin first began to form in response to the separation of Africa from North America (see *Oceanus*, Vol. 17, No. 3). Movement of these older rocks influences the processes important in hydrocarbon formation, and probably causes the pattern of earthquake occurrence along the margin seaward of mountain belts.

**Methods of Investigation**

Seismic reflection and refraction are two of the most important methods used in developing continental margin models. Both techniques use sound energy that is sent into the sea floor (see *Oceanus*, Vol. 20, No. 2, Spring 1977, p. 40). From the refraction technique, the velocity of sound can be estimated for the various layers of sedimentary rocks in the basin and for the underlying igneous and metamorphic rocks; the difference in velocities allows one to estimate the types of rocks that make up the various layers. The seismic reflection profiles approximate a geological cross section by enabling one to trace layers within the sediment-filled basins. These reflectors are the returns of the sound waves from a horizon across which there is a rapid change in physical properties — for example, the change



from a sequence of limestone to shale, or across an old, buried erosional surface.

With the exception of those collected by the oil industry, most seismic reflection profiles through 1972 consisted of single-channel data, which provided information about the upper few kilometers of sediments. In collection of single-channel data, sound rays are directed straight down and returns are reflected straight back from shallow reflectors. For multi-channel data, sound rays passing through the rock layers at varying angles are picked up by the many listening devices in a 3½-kilometer-long hydrophone, and fed into a 48-channel tape recorder. A computer sums coherent returns recorded on the tape and redisplays them to provide a profile, showing the approximate arrangement of rock layers along the ships' cruise track. Since 1973, a substantial number of multi-channel seismic reflection profiles have been collected off the eastern coast of the United States by the U.S. Geological Survey (USGS), the Woods Hole Oceanographic Institution (WHOI), and the University of Texas. These profiles have enabled scientists to explore much deeper into the margin, discerning sedimentary and basement structure at depths as great as 15 to 20 kilometers.

During the last six years, the USGS has collected 20,000 kilometers of multi-channel profiles over the U.S. Atlantic margin, providing a cross-shelf line spacing of about 40 kilometers. Besides giving the shapes of the offshore basins and platforms, the multi-channel data are helpful in locating traps that might contain hydrocarbons.

Magnetic data also were collected over the U.S. Atlantic margin using seaborne and airborne magnetometers. Magnetic data were obtained across the slope and upper continental rise, providing a grid of 185,000 kilometers of profiles. This grid extends from Florida to Georges Bank. Analysis of the earth's magnetic field over the entire margin has disclosed many anomalies (deviations from the earth's magnetic field), which are probably caused by changes in the composition of deeply buried igneous and metamorphic rocks.

Early gravity measurements along the U.S. Atlantic margin were made by pendulum systems aboard submarines. By the late 1960s, improved surface ship gravimeters increased the quality and quantity of collected data. Free-air gravity anomaly maps of the Atlantic continental margin at contour intervals of 20 and 25 milligal* were published in the early 1970s by Carl Bowin of WHOI and others. More recently, U.S. Navy and U.S. Geological Survey data have been compiled to provide a free-air gravity anomaly map contoured at an interval of 10 milligal; gravity measurements along the Atlantic margin were obtained in 1975–1976 as part of a 39,000 kilometer survey by the USGS and WHOI, using a vibrating string shipboard gravimeter developed by Bowin and his associates.

## Marginal Basins and Platforms

Adjacent to the eastern United States are four sediment-filled basins or troughs and three platforms (Figure 1). One of these is the Blake Plateau basin. It contains more than 13 kilometers of sediments, and is probably underlain by a broad zone of transitional crust (Figure 2). The character of the magnetic anomalies suggests that this crust is neither typically oceanic nor continental. After continental breakup, a thick sequence (6 to 8 kilometers) of Jurassic-age (some 180 million years ago) sediments accumulated over transitional and early formed oceanic crust. During the subsequent Cretaceous Period (100 million or so years ago), a thinner sequence of limey sediment was deposited.

The margin east of the Carolinas and south of Cape Hatteras consists of a shallow platform under the shelf and inner Blake Plateau, and a narrow, deep trough (Carolina trough) under the upper slope. Sediments on the Carolina platform are less than 4 kilometers thick, whereas they are more than

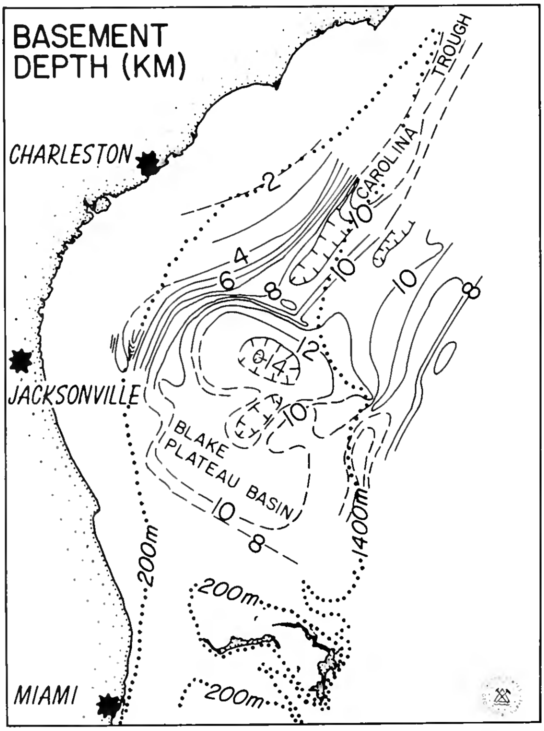


*Figure 2. Depth in kilometers to post-rift erosion surface for the Blake Plateau basin that formed mainly over older crystalline rocks following breakup of Africa and North America.*

---

*A unit of acceleration equivalent to 1/1000 gal or 10 microns per second that is approximately one millionth of the normal acceleration of gravity at the earth's surface.

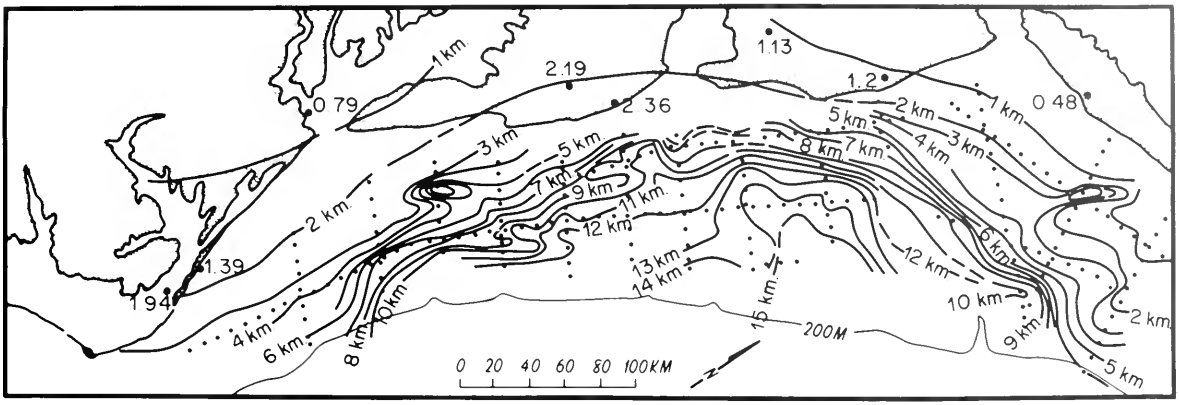


*Figure 3. Sediment thickness (kilometers) for Late Triassic (?) and younger sedimentary rocks within the Baltimore Canyon trough.*

10 kilometers thick in the Carolina trough — a narrow feature inferred mainly from magnetic and seismic data.

The Baltimore Canyon trough is an elongated basin that thickens to the northeast where sediments are in excess of 17 kilometers thick (Figure 3). The closeness of contours indicates that the thickness of sediment changes most rapidly under the inner continental shelf. The thickness contours are irregular toward both the Carolina platform and Long Island platform because the basement crustal rocks have been faulted into grabens (downdropped blocks) and horsts (upraised blocks between grabens). Thickness contours are not completed around the seaward side of the trough, because the basement rocks cannot be delineated there.

The Long Island platform is one of several regions along the Atlantic continental margin where rifted shallow crust is buried by only a thin layer of sediments; the platform is just landward of the contiguous sedimentary basins. As shown in Figures 3 and 4, the sedimentary wedge is about 4 kilometers thick, but underlying rifts (grabens) filled with thick Triassic (about 200 million years old) sediments increase the total sediment accumulation to more than 9 kilometers.

The Georges Bank basin is a rectangular basin situated between the La Have and the Long Island platforms (Figure 4). On multi-channel reflection profiles, the acoustic basement is lost near the shelf edge, but magnetic data indicate that an igneous ridge may be as shallow as 6 kilometers below sea level seaward of the basin axis. To the northeast, a thinner sequence of sediments is found overlying block-faulted basement rocks that rise to form the La Have platform. To the northwest, thinning occurs in a somewhat simpler manner on the Long Island platform.

### Developmental Stages of the Atlantic Margin

Though the basins and troughs adjacent to the platforms have different outlines, multi-channel seismic reflection profiles indicate similar stages of development. The two main stages are (1) a rift phase during the initial thinning of continental crust, followed by (2) a subsidence phase during continental separation.

As mentioned previously, the platforms have a fairly thin sediment cover, being the sites of

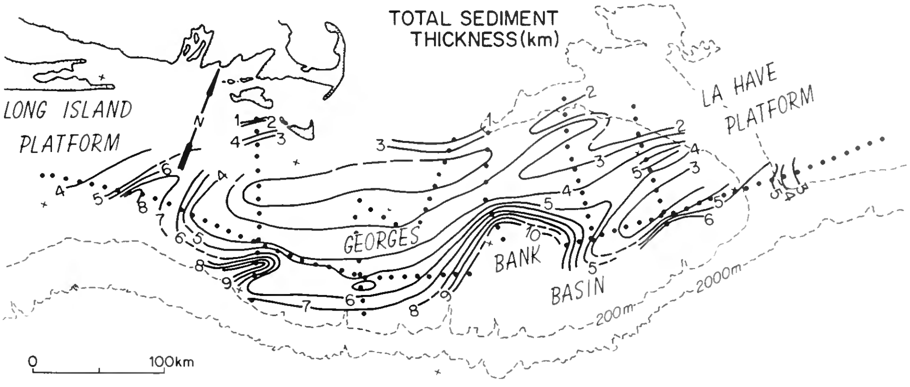


*Figure 4. Sediment thickness for Late Triassic (?) and younger sedimentary rocks within the Georges Bank basin.*

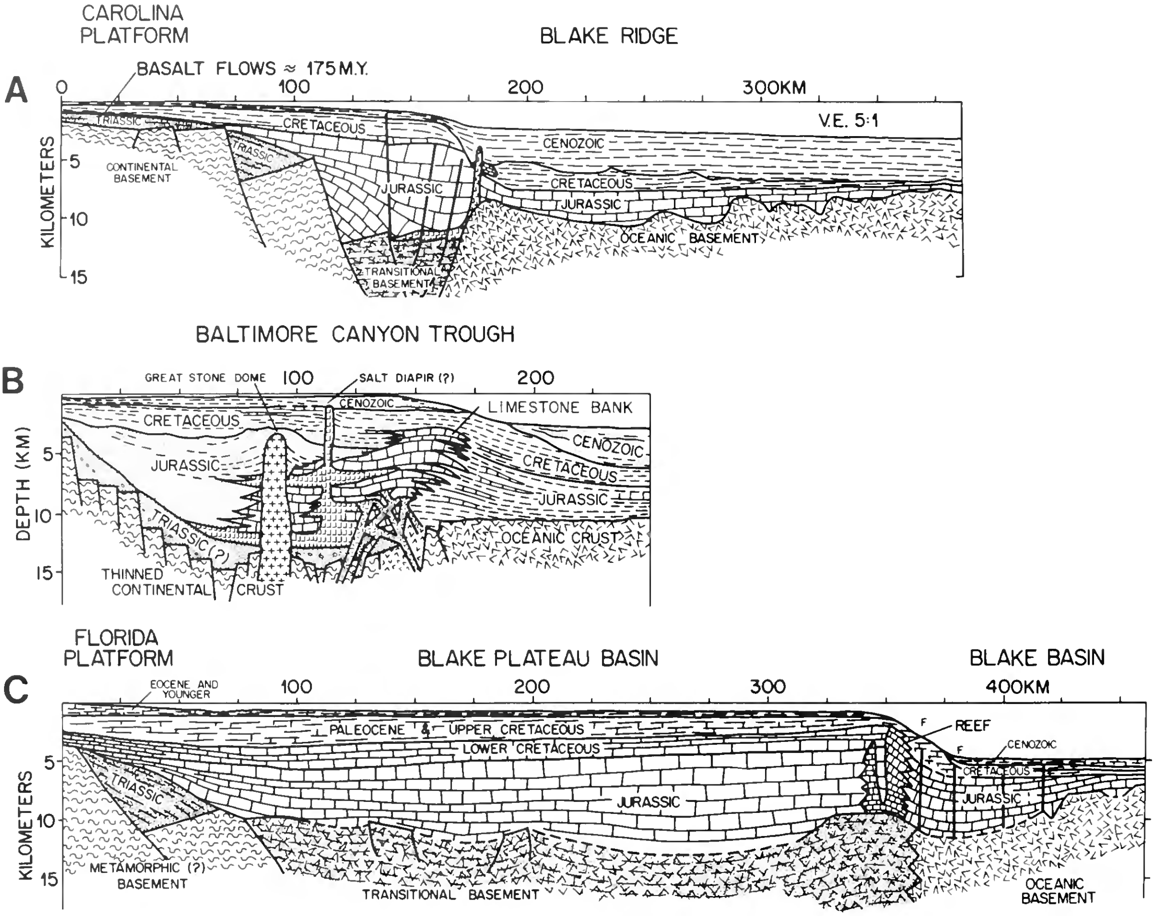


*Figure 5. The Carolina platform and trough along the Blake Outer Ridge (A), the Baltimore Canyon trough (B), and the Blake Plateau basin (C). Sections are based on an integration of geophysical profiles and nearby drill hole data.*

numerous horsts and grabens that probably were formed during the Triassic Period (Figure 5A). They are the most seaward protrusions of pre-Jurassic continental crust and were not greatly affected by subsequent block-faulting and subsidence during the Jurassic Period. Some platform areas, such as those at Cape Hatteras and Long Island, extend across the continental margin to separate the major basins. As shown by the grabens and horsts, the southwest and northeast edges of the platforms probably represent irregularities in the pattern of crustal breakup, which resulted in major faults or fracture zones (Figure 6).

During the earliest stages of margin development off the southeastern United States (Figure 5A), rifting (Triassic Period) produced a rough topography, resulting in a flood of continental deposits. The strata were tilted seaward and beveled as the newly forming margin subsided. Volcanic flows covered the landward part of these deposits about 175 million years ago; as the margin subsided, a wedge of marine Upper Jurassic and Cretaceous Period sediments formed the continental shelf.

Beneath the Carolina trough and extending over a narrow crustal transition zone, the sedimentary rocks are cut by growth faults (crustal offsets that grew during sediment deposition) and intruded by salt (?) diapirs.* The latter are found in a narrow zone as far as 200 kilometers north of the profile, along the outer edge of the Carolina trough. They probably originated from the flowage of deeply buried evaporitic sediments that were deposited in a narrow, restricted seaway shortly after Africa and North America separated. Salt flowage probably contributed to the formation of growth faults, when the overlying sedimentary rocks adjusted by downdropping. Farther north off the Long Island platform, the sedimentary cover also is thickened under the slope, but the diapirs and growth faults are absent. Seaward of the Carolina trough, the profile lies along the Blake Outer Ridge, where the youngest sediments (Cenozoic— less than 65 million years) are as much as 5 kilometers thick.

---

*A dome-like fold resulting from a mobile core of salt that has broken through the more brittle overlying rocks.

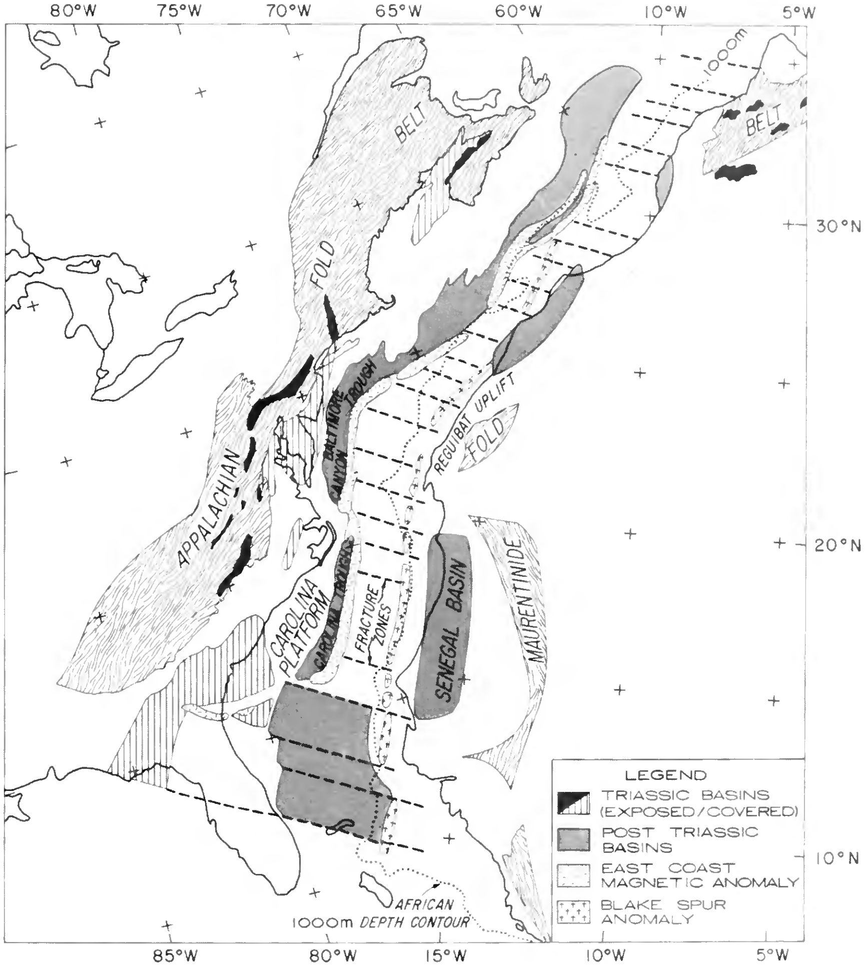


*Figure 6. The North Atlantic about 175 million years ago (Blake Spur anomaly time). (Adapted from Schouten and Klitgord, 1977)*

A cross section of the northern part of the Baltimore Canyon trough (Figure 5B) indicates that it is probably built across a zone of rifted, thinned continental or transitional crust that lies landward of initial oceanic crust and a probable zone of intrusive igneous rocks. The sediments that fill the trough have been penetrated and domed by an igneous intrusion (Great Stone Dome) of Early Cretaceous age. The section crosses the widest (150 kilometers) and deepest (14 to 15 kilometers) part of the trough.

In Figure 5B, the main limestone bank or reef mass of Jurassic-Early Cretaceous age is close to the area of intrusions. If the coastal shelves of the Red Sea are any example (see page 33), then limestone beds could directly overlie basalts and older sediments, and reef buildup could be expected. The relationship between water depth and basement configuration is of key importance. If crustal blocks (continental-volcanic) lay in sufficiently shallow water during the early rifting stage, and if water temperature, salinity, and turbidity conditions were favorable, then carbonate bank growth could have started. If so, subsidence of basement blocks during the Jurassic and Early Cretaceous does not appear to have exceeded possible bank buildup or reef growth rates needed to keep the water shallow.

The Blake Plateau basin in Figure 5C shows an evolutionary pattern similar to that in the north (Figure 5A), except that the zone of transitional basement is much wider, and reef growth provided a dam for sediments until approximately the middle of Cretaceous time. Landward, the Florida platform was probably built over block-faulted continental crust, containing rift deposits of Triassic age. Seaward of the basin is oceanic crust created in the last 170 million years as North America separated from Africa. One can see in Figure 5C that the main period of basin subsidence and filling was during the Jurassic Period, when limestone as thick as 8 to 9 kilometers accumulated there, bordered by reefs on the seaward side. It was concluded from study of two Deep Sea Drilling Project (DSDP) holes, which penetrated lower Cretaceous reef limestones, that a similar environment continued into the Early Cretaceous. Analyses of the sedimentary rocks found in the holes indicate that the locus of reef limestone deposition moved slightly westward during the middle Cretaceous, then probably died out. During the Late Cretaceous, in response to a long-term rise in sea-level, the shelf edge moved 300 kilometers west to the Florida platform. Beginning in the Tertiary Period (about 65 million years ago) the Blake Plateau was affected by erosion or reduced deposition when the flow of the Gulf Stream shifted to the west. Subsidence of the continental margin, combined with reduced sedimentation, resulted in the present physiography of the Blake Plateau — a submerged platform 600 to 1,000 meters deep. Landward, the present continental shelf edge was formed by sediment buildup against the flank of the fast flowing Gulf Stream during the Cenozoic Era.

### Paleogeographic Reconstructions

Studies of magnetic anomalies have allowed scientists to outline the main structural and crustal features of the Atlantic margins and thus to fit the continents back together (Figure 6). The largest of these anomalies is the East Coast Magnetic Anomaly (ECMA), which is a long, continuous magnetic high located near the shelf edge from South Carolina to Nova Scotia. Much lower amplitude linear magnetic anomalies are present seaward of the ECMA, and these are attributed to the generation of new crust by sea-floor spreading. Over margin platforms where continental crust is shallowly buried, a pattern of high-amplitude, short-wave length magnetic anomalies is characteristic. Over sedimentary basins landward of the ECMA, a pattern of broad, intermediate-amplitude, non-linear magnetic anomalies is typical. The sources of these anomalies are probably volcanic and metamorphic basement rocks.

In the Atlantic oceanic basin, sea-floor spreading magnetic lineations provide age markers by which the relative positions of the Americas and Africa can be determined. Using these markers and the fracture zones within the oceanic crust, we can move Africa and North America back toward each other. In Figure 6, the reconstruction dates to 175 million years ago, when the continents were slightly separated, and the mid-oceanic ridge, where new oceanic crust was being created, was along the Blake Spur Anomaly (BSA). The original zone along which initial separation occurred lies landward of the ECMA on the American margin; a matching anomaly beneath the African margin has not been found.

Both the African and North American margins are made up of a series of offshore sedimentary basins that border an older Paleozoic Era (225 to 600 million years ago) fold belt (Appalachians and Mauritanides). The margin and bordering coastal area are more complex on the North American side because a series of Triassic rift basins exists between the older mountain belt and the offshore area. A long period of crustal stretching preceded final separation of the continents and most of the stretched crust ended up on the North American side of the break as a series of Triassic basins (black and vertical strip pattern — Figure 6) landward of the present margin.

In the African-North American reconstruction, platforms or upraised areas on one side are opposite basins or troughs on the other side (Figure 6). The Senegal basin is opposite the Carolina platform and a narrow Carolina trough, and the Baltimore Canyon trough is opposite the Reguibat uplift.

A comparison of the two margins shows that results of crustal separation have been similar. Both margins are characterized by a string of deeply subsided offshore sedimentary basins. Though we have not discussed the African basins, they are composed of sedimentary rocks similar to those found in North American basins, and they are built over a rifted foundation of older continental crust. The basins show the transition upward from terrestrial red beds (red sandstone, shale, and conglomerates) of Triassic age, through shallow-water limestones of Jurassic and Early Cretaceous age, to marine and deltaic sediments of Late Cretaceous and Cenozoic age.

### Interpretation for the Future

After rifting and separation of North America and Africa, cooling of the lithosphere resulted in rapid subsidence of the major basins along the U.S. Atlantic shelf (Figure 7A). Initially, the oldest sediments probably accumulated in faulted basins above sea level, and then as the entire region subsided, sediment began to deposit in lagoons, on alluvial plains, and in deltas; with time, the depositional areas became more marine, as evaporitic sediment and lime muds accumulated (Figure 7B). A series of carbonate banks built up along much of the continental margin over crustal blocks that developed during early stages of rifting (Figure 7C). Ultimately, the banks were overwhelmed by Cretaceous sediment. However, these are thinner (4 kilometers or less in the Baltimore Canyon trough) than the Jurassic rocks (8 to 10 kilometers in the same area) that filled the basin during the initial, more rapid phase of subsidence.

In the Blake Plateau basin, the early phase of sedimentation resulted in the deposition of evaporites and open marine shelf carbonates that interfinger with nonmarine sedimentary rocks toward the Carolina platform and Southeast Georgia embayment.

North of the Blake Plateau, sediments from the Cretaceous Period advanced seaward over the former carbonate shelf edge, initiating extensive sedimentation over the slope and rise. In the same area of the margin, during the Cenozoic Era, a prominent continental rise wedge was deposited

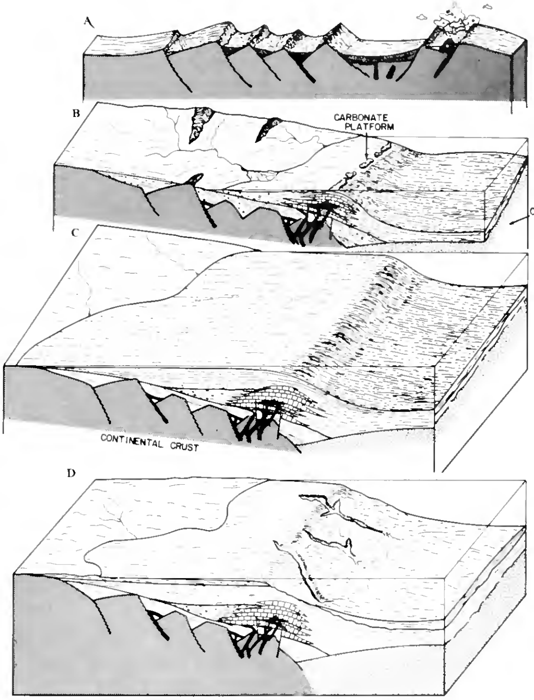


*Figure 7. Stages in the development of Atlantic-type margins. Stage A shows the rift phase, whereas B-D show the subsidence phase as it has developed in the Baltimore Canyon trough area.*

along much of the continental margin, while the slope was being cut back 10 to 30 kilometers in several phases of erosional retreat (Figure 7D). Farther south, the Blake Plateau existed as a shallow Bahama-like shelf into the middle Cretaceous; fringing reefs bordered the eastern edge of the plateau. Then, as mentioned earlier, the slope-shelf break shifted 300 kilometers to the west near the Florida platform, and the Blake Plateau became a site for deep-water sedimentation (the present depth range is 600 to 1,100 meters).

This interpretation of geological and geophysical data provides a summary of the structural and sedimentary history of the U.S. Atlantic margin. Since the outer continental shelf is the current frontier for hydrocarbon exploration, a better understanding of its development may improve our chances of finding and exploiting this much needed resource.

*John S. Schlee is a geologist with the U.S. Geological Survey, Office of Marine Geology, Atlantic/Gulf of Mexico Branch, Woods Hole, Massachusetts. David W. Folger is chief of the branch office at Woods Hole. William P. Dillon is a geologist, and Kim D. Klitgord and John A. Grow, geophysicists in the same office.*

### Acknowledgment

We gratefully acknowledge the suggestions and critical review of our colleagues in preparing this article. In particular, Richard J. Wold, Mahlon M. Ball, and Susan Schlee made many excellent comments to improve the text. Illustrations were prepared by Patricia Forrestel and Lin Sylwester.

### Selected Readings

Dillon, W. P., C. K. Paull, R. T. Buffler, and J. P. Fail. 1979. Structure and development of the Southeast Georgia Embayment and northern Blake Plateau: preliminary analysis. In *Geological and geophysical investigations of continental margins,* ed. by J. S. Watkins, L. Montadert, and P. W. Dickerson. *Am. Assoc. Petroleum Geologists Memoir* 29: 27-41.

Emery, K. O., and E. Uchupi. 1972. Western North Atlantic ocean: topography, rocks, structure, water, life and sediments. *Am. Assoc. Petroleum Geologists Memoir* 17: 532.

Emery, K. O., E. Uchupi, J. D. Phillips, C. O. Bowin, E. T. Bunce, and S. T. Knott. 1970. Continental rise of eastern North America. *Am. Assoc. Petroleum Geologists Bull.* 54: 44-108.

Ewing, J., and F. Press. 1950. Crustal structure and surface wave dispersion. *Seismological Soc. of Amer. Bull.* 40: 271-80.

Ewing, J., and M. Ewing. 1959. Seismic refraction measurements in the Atlantic ocean basins, in the Mediterranean Sea, on the mid-Atlantic ridge, and in the Norwegian Sea. *Geol. Soc. America Bull.* 70(3): 291-318.

Ewing, M., A. P. Crary, and H. M. Rutherford. 1937. Geophysical investigations in the emerged and submerged Atlantic coastal plain. Part I, Methods and results. *Geol. Soc. America Bull.* 48: 753-801.

Ewing, M., G. P. Woollard, and A. C. Vine. 1940. Geophysical investigations in the emerged and submerged Atlantic coastal plain. Part IV, Cape May, New Jersey section: *Geol. Soc. America Bull.* 51: 1821-40.

Grow, J. A., R. E. Mattick, and J. S. Schlee. 1979. Multi-channel seismic depth sections and interval velocities over the continental shelf and upper continental slope between Cape Hatteras and Cape Cod. In *Geological and geophysical investigations of continental margins,* edited by J. S. Watkins, L. Montadert, and P. W. Dickerson. *Am. Assoc. Petroleum Geologists Memoir* 29: 65-83.

Heirtzler, J. R., G. O. Dickson, E. M. Herron, W. C. Pitman III, and X. LePichon. 1968. Marine magnetic anomalies, geomagnetic field reversals, and motions of the ocean floor and contents. *Jour. Geophysical Research* 73: 2119-36.

Klitgord, K. D., and J. C. Behrendt. 1979. Basin structure of the U.S. Atlantic continental margin north of Cape Hatteras. In *Geological and geophysical investigations of continental margins,* edited by J. S. Watkins, L. Montadert, and P. W. Dickerson. *Am. Assoc. Petroleum Geologists Memoir* 29: 85-112.

Pitman, W. C. III, and M. Talwani. 1972. Sea-floor spreading in the North Atlantic. *Geol. Soc. American Bull.* 83: 619-46.

Pourtales, L. F. 1872. The characteristics of the Atlantic sea bottom off the coast of the United States. *Report by the Supt. of U.S. Coast Survey for 1869, App. II:* 220-25.

Ryan, W. B. F., M. B. Cita, E. L. Miller, D. Hanselman, W. D. Nesteroff, B. Hecker, and M. Nibblelink. 1978. Bedrock geology in New England submarine canyons. *Oceanologica Acta* 1: 233-54.

Schlee, J. S., J. C. Behrendt, J. A. Grow, J. M. Robb, R. E. Mattick, P. T. Taylor, and B. J. Lawson. 1976. Regional framework off northeastern United States. *Am. Assoc. Petroleum Geologists Bull.* 60: 926-51.

Scholle, P. A., ed. 1977. Geologic studies on the COST B-2 well, U.S. mid-Atlantic Outer Continental Shelf. *U.S. Geol. Survey Circ.* 750: 71.

Schouten, H. and K. D. Klitgord. 1977. Map showing Mesozoic magnetic lineations, western North Atlantic. *U.S. Geol. Survey Misc. Field Studies Map MF-915.* scale 1: 2,000,000.

Sheridan, R. E. 1974. Conceptual model for the block-fault origin of the North American Atlantic continental margin geosyncline: *Geology* 2: 465-68.

Taylor, P. T., I. Zietz, and L. S. Dennis. 1968. Geologic implications of aeromagnetic data for the eastern continental margin of the United States. *Geophysics* 33: 755-80.

Worzel, J. L., and G. L. Shurbet. 1955. Gravity anomalies at continental margins. *National Acad. Science Proc.* 44: 458-67.

# The Evolution of the

### by Floyd W. McCoy and Philip D. Rabinowitz

Almost a hundred years ago, the German geologist Eduard Suess suggested that at one time there was no South Atlantic Ocean. In its place, he thought, was a huge continent: a combination of Africa and South America — Gondwanaland. Triggered by this startling idea, research continues on this outstanding example of an evolving ocean basin. Also of interest is the economically significant result of the ocean's development: great marginal basins, one of our largest sources of petroleum.

It was not economic considerations but the geographic fit between coastlines of the African land mass and South America that first intrigued Suess, and later another German scientist, Alfred Wegener. Scientists now point to many other correlations between South America and Africa. Outcrops on both continents indicate similar rocks, fossils, and even land forms — cliffs, flat-topped peaks, deserts, mountains.

Information from outcrop generally provides a horizontal geologic picture, representing numerous cuts or time slices of the earth's history, whereas the boundary or margin between a continent and an ocean is a vertical separation, representing a more finite episode in geological time. Continental margins are studied in a number of varied ways. One is to note their effects upon the earth's gravity and magnetic fields. Another utilizes remote sensing using seismic techniques. And still another incorporates direct observations through drilling and sampling of rock outcrops. Application of these methods has significantly contributed to our understanding of the evolution of the South Atlantic, where the concept of continental drift suggested by Suess and Wegener was based upon opposing continental margins that appear to have changed little during some 130 million years or more of the earth's recent history.

South Atlantic margins are considered passive, trailing behind the continent as continental drift occurs. Because of their passivity and the preservation of many features that record the splitting apart of Gondwanaland, the earth's history can be reversed and the two continents rejoined, as was done by Sir Edward Bullard about a decade ago (Figure 1).

In such a classic area as the South Atlantic, continental margins can be portrayed by discussing marginal development through geological time in a series of three time slices, all of which depict various characteristics in the initial formation of this margin during the Cretaceous Period (180 to 65 million years ago) of the Mesozoic Era.

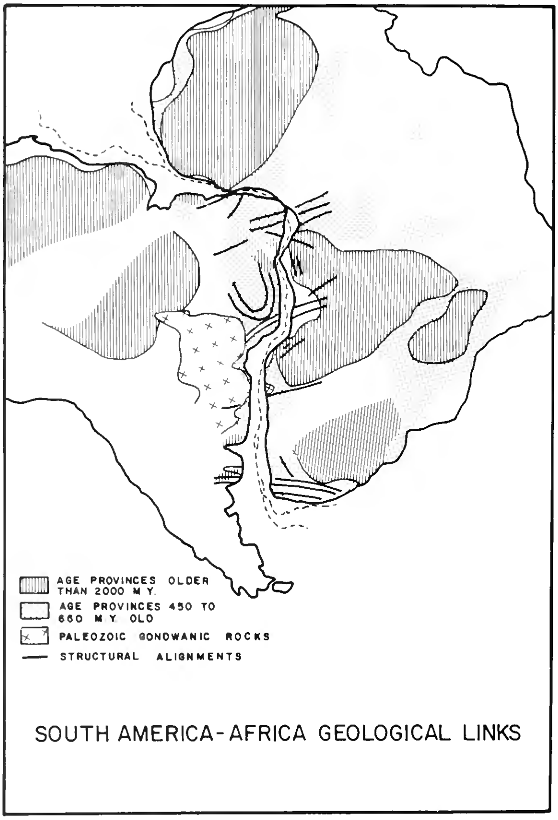


*Figure 1. Pre-continental drift reconstruction of South America and Africa into Gondwanaland — the so-called Bullard fit, using the modern 500-meter isobath as the basis for rejoining the continents. Also shown are various geological links between the continents. (After Asmus and Ponte, 1973; and Bullard, and others, 1965)*

### Early Development: ~ 180 to 130 Million Years Ago

Initial pre-oceanic rifting processes probably occurred in the Early Cretaceous-Late Jurassic (about 180 million years ago), when deep crustal movements formed a north/south rift zone through Gondwanaland. At this stage, the rift valley was narrow with numerous volcanoes and lakes, probably similar to modern conditions in the East Africa rift zone. A continent/ocean boundary was incipient, but indistinct. As these tectonic processes continued for some 45 million years, the rift enlarged and deepened sufficiently. By about 130 million years ago, in the Early Cretaceous, the ocean transgressed into the valley, forming a linear seaway (Figure 2) — thus an ancient continental arrangement, one that had existed during the Paleozoic Era and much of the Mesozoic Era, was irreversibly altered. The modern arrangement we live with today was initiated.

A distinct ocean/continent boundary existed beneath the seaway. Evidence for this comes from the history preserved in rock outcrops on land, in buried sea-floor sedimentary deposits, and in their magnetic properties. In total, this evidence represents a physical environment of a hundred or more million years ago. By studying the arrangement of magnetic anomaly sequences, local patterns can be deciphered with respect to this worldwide history. Applying this criteria to the South Atlantic, the earliest oceanic crust identifiable in the South Atlantic is 130 million years old or Early Cretaceous, the age of the oldest identifiable magnetic anomaly. Interestingly, the date for the formation of these earliest sea-floor deposits is in close chronological agreement with large volcanic eruptions of basalts poured out onto the adjacent continental borderlands in Southwest Africa-Namibia (125 million years ago), and Brazil (115 to 135 million years ago).

Oceanic crust within the rift was relatively thin, but thickened or elevated along the continent/ocean boundary. These transitional zones (see page 2) may be relics of the very early stages of rifting, when volcanic material of composition similar to oceanic crust was emplaced at relatively higher levels than the elevations of whatever mid-oceanic ridges existed then.

At this stage of development, a terrestrial fauna, dominated by large reptiles, continued to have convenient access between the two continental portions north of the still-narrow seaway. The physiography was similar to that of the modern Red Sea (see page 33).

This earliest marine segment of the South Atlantic was shallow in comparison to today's depths, and was covered with calcium carbonate-rich sediments and clays. However, north of the seaway, the rift — not yet sufficiently deepened to allow the sea to transgress — contained lake sediments, non-marine red sandstones, and thick piles of conglomerates.

### Massive Salt Deposition: ~ 105 Million Years Ago

Non-marine deposits found in outcrops from the land bridge between the North and South Atlantic indicate an oceanic connection was not made;

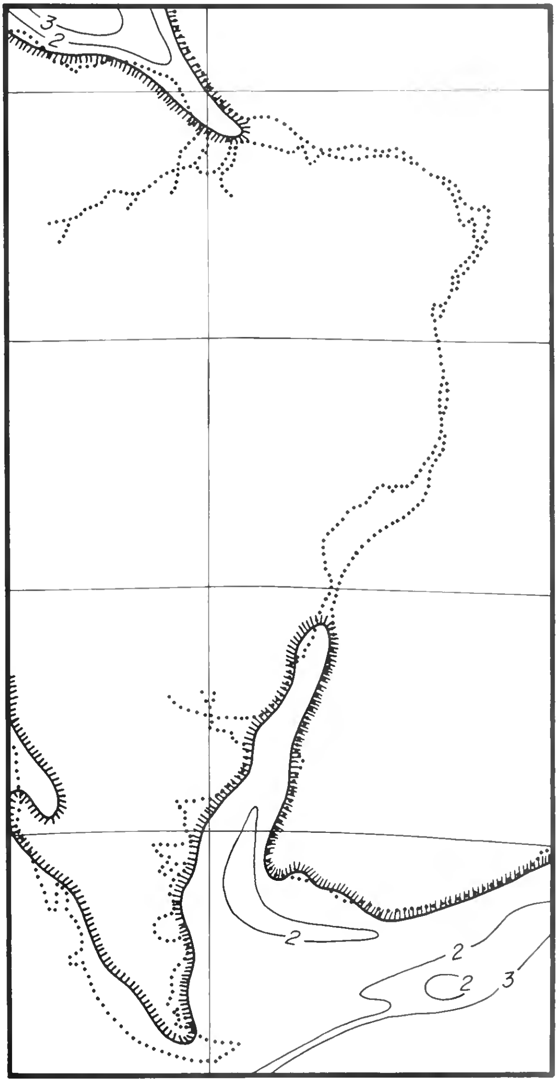


*Figure 2. Early development of the South Atlantic Ocean and its margins about 130 million years ago (Early Cretaceous). Ancient coastlines of this time period are shown as solid hatched lines; for comparison, today's coastlines are depicted by dotted lines. The extent and size of marginal basins in this time slice (as well as in the time slices of Figures 3 and 5) are noticeable by comparing coastlines. Paleobathymetry is in kilometers with the 1-kilometer paleoisobath omitted along continental margins. (After McCoy and Zimmerman, in preparation)*

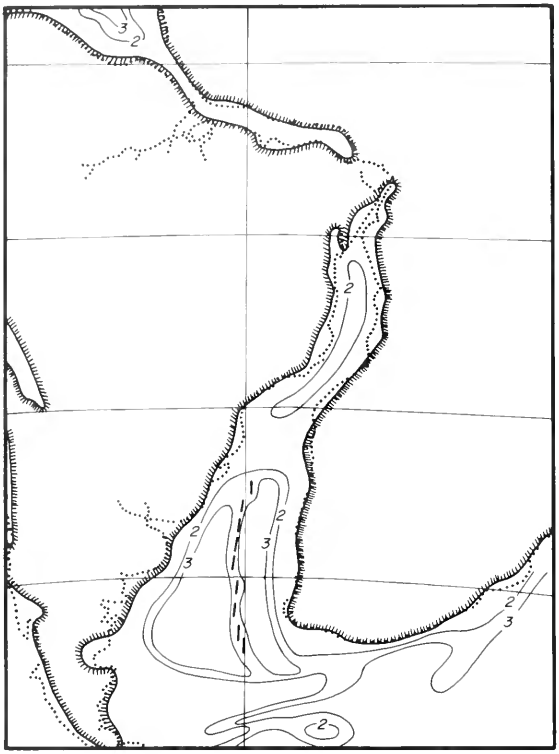


*Figure 3. Geographic and bathymetric development of the South Atlantic about 105 million years ago (earliest Cretaceous). The submarine protrusion eastward from the tip of South America is the ancestral Falkland Plateau, a portion of the South American continent that formed a sill across the southern end of the early South Atlantic Ocean. Another sill crossed the ocean midway, a feature that was to evolve into our modern São Paulo Plateau — Rio Grande Rise (off South America) and Walvis Ridge (off Africa); it was north of this sill that extensive salts were deposited. The mid-oceanic spreading center is portrayed by heavy dashed lines. Other symbols are the same as those in Figure 2.*

reptilean fauna still had passage between the two continental fragments. At this time, the seaway occupied a considerably deepened rift valley, extending farther north into equatorial latitudes (Figure 3).

Physiographically, the ocean floor was divided into a series of three basins. The two southern basins were divided by a broad north/south ridge, the precursor of the modern Mid-Atlantic Ridge. An east/west sill (the modern Falkland Plateau) south of these two basins somewhat isolated them from the world ocean circulation patterns, particularly with respect to deep-water movements. Another east/west sill, between the two southern basins and the northern trough (the modern Rio Grande Rise-Walvis Ridge) similarly influenced oceanic conditions in the northern trough.

Landlocked on three sides and blocked by the Rio Grande Rise-Walvis Ridge, evaporation in excess of precipitation occurred in the arid, equatorial northern basin, resulting in the deposition of massive salt layers. These salts mantled both oceanic and continental crust, the latter in marginal basins. Seismic profiles indicate that these salt deposits have now shifted and have been contorted into diapirs (disturbed vertical salt domes), which form economically important traps for gas and oil (Figure 4).

Salt deposition did not last for more than a few million years. As continental separation continued and environmental conditions changed, salts were no longer deposited. The massive salt layers, in fact, were split apart by the movement of their respective continental margin areas, forming an important isochron (geological time line) that is

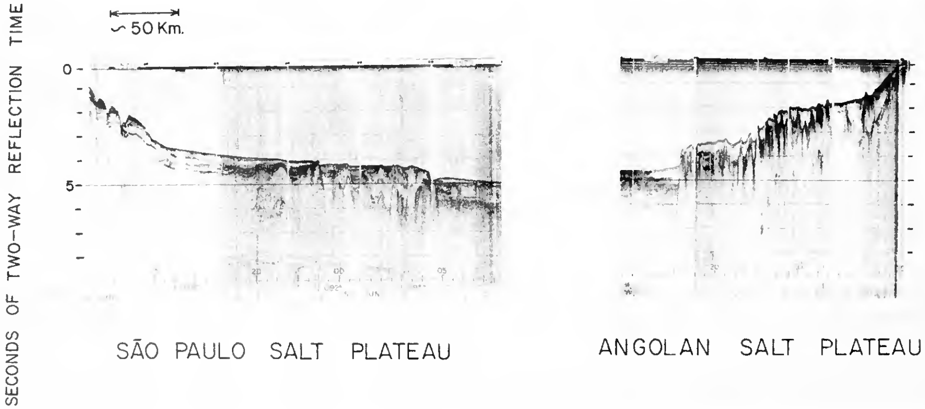


*Figure 4. Salt deposits in the subsurface beneath the continental margins and within the oceanic crust as depicted by seismic profiling. Intense deformation of the originally flat salt layer produced the "spiked" appearance in the seismic records. These are salt diapirs or domes shown with a large vertical exaggeration. The vertical scale is in seconds of two-way reflection time (from the sound source to the subbottom reflector, then back to the recorder that printed the record), whereby 1 second corresponds to approximately 750 meters vertical depth. (Rabinowitz and LaBrecque, in press)*

important in reconstructing the history of the South Atlantic Ocean.

### North/South Connection: ~ 86 Million Years Ago

About 20 million years after the salt deposition, continued enlargement of the ocean basin allowed a permanent connection between the South and North Atlantic to be established (Figure 5). The best evidence of this comes from sediment distributions in marginal basin outcrops and from oceanic drilling.

An additional seaway — the temporary, shallow, Benue Trough — existed on continental crust across North Africa, produced in part by large sea-level transgressions over this remnant of ancient low-lying Gondwanaland (see page 71).

East/west sills continued to restrict deep-water movement; the South Atlantic bottom water circulation was sluggish, causing stagnation and leaving distinctive sequences of black shales that are presently traceable in drilled cores throughout all four of the abyssal South Atlantic basins. The western section of the southernmost sill, the Falkland Plateau, was the seaward terminus of a huge marginal basin (Figure 5, lower left) that extended onto southern South America as far as the Andes Mountains, which were being uplifted because of the collision between the South American lithospheric plate and the Pacific plate. Thus an active Pacific-type margin dumped its erosional debris onto a passive margin, debris that included organic matter, which later formed petroleum reserves.

And so, by about 86 million years ago, the split was complete; ocean/continent boundaries were formed along all margins of the South Atlantic — the ocean was not isolated but part of a new, extensive meridonal basin, the Atlantic Ocean.

### Some Final Thoughts on the Fit

The South Atlantic has intrigued scientists for decades — from Suess and Wegener to Bullard to many researchers today. This archetypal example of the development of an ocean basin by continental drift is particularly well displayed by Bullard's interpretation, where the small irregularities in refitting continental margins seem remarkably slight considering the millions of years of erosion and deposition along these margins. This, however, emphasizes an important point: such continental margins preserve ancient events with little modification. Technically, they define an ocean/continent boundary. In addition to the remarkable mesh of these margins is the geological link of older rocks, fossils, structural alignments, and even some ancient physiographic features that are found on the two opposing land masses, which are today separated by a vast ocean.

The evolution of the border zone between continental and oceanic crust remains an active field of research, prompted by the economic and political attention now being focused on this area in the race to uncover new petroleum resources. As these evolutionary aspects become more clearly understood, there will emerge a broader knowledge of the tectonic and paleoenvironmental conditions that prevailed in the South Atlantic.

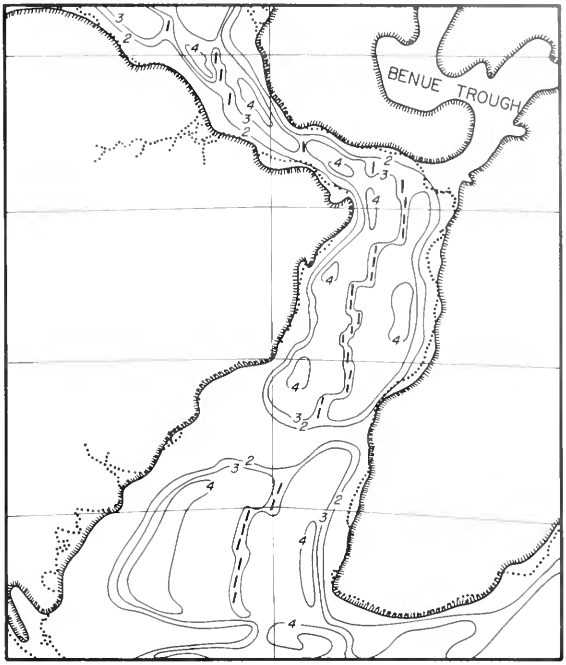


*Figure 5. Development of the South Atlantic about 86 million years ago (middle Cretaceous). The opening between the northern and southern portions of the Atlantic Ocean in equatorial areas produced a distinct shear because of the dominant east/west movement between the continents. Long, high submarine ridges accompanied this shearing. (After McCoy and Zimmerman, in preparation)*

*Floyd W. McCoy is a Research Associate and Curator of Geological Samples at the Lamont-Doherty Geological Observatory of Columbia University, New York. Philip D. Rabinowitz is a Senior Research Associate at the Observatory.*

#### References

Asmus, H.E., and F.C. Ponte. 1973. The Brazilian marginal basins. In *The ocean basins and margins*, edited by E.A.M. Nairn and F.G. Stehl, pp. 87-133. Vol. 1, The South Atlantic. New York: Plenum Press.

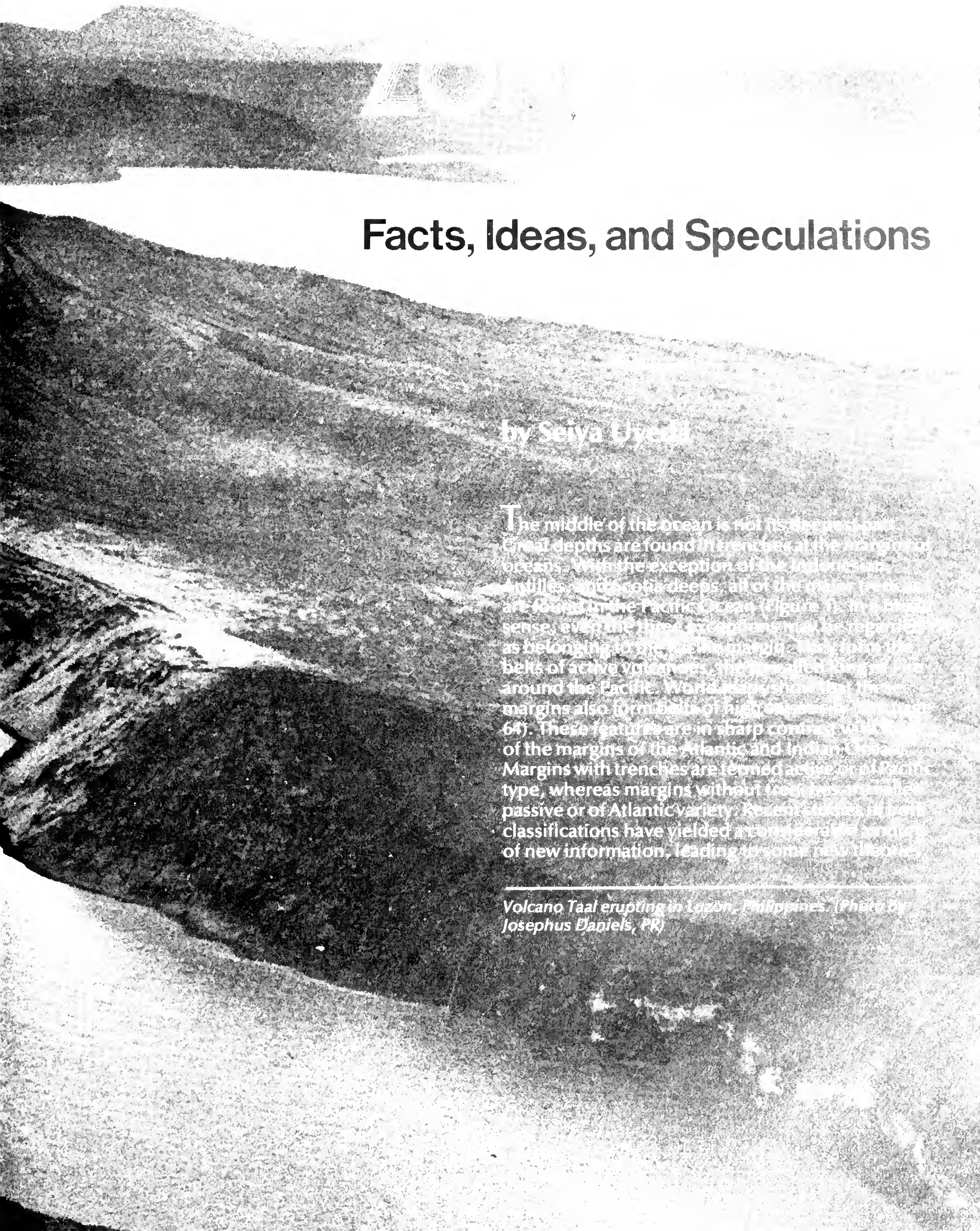
Bullard, E., J.E. Everett, and A.G. Smith. 1965. The fit of the continents around the Atlantic. In *A symposium on continental drift*, Royal Soc. London, Philos. Trans., Vol. 258:41-51.

McCoy, F.W., and H.B. Zimmerman. 1977. A history of sediment lithofacies in the South Atlantic Ocean. *Initial reports DSDP* 39:1047-80.

Pitman, W.C., III, R.L. Larson, and E.M. Herron. 1974. *The age of the ocean basins.* Boulder, Colo.: Geol. Soc. America.

Rabinowitz, P.D., and J. LaBrecque. In press. The Mesozoic South Atlantic Ocean and evolution of its continental margins. *J. Geophys. Res.*

———. 1977. The isostatic gravity anomaly: a key to the evolution of the ocean-continent boundary at passive continental margins. *Earth and Planetary Sci. Letters* 35:145-50.



# Facts, Ideas, and Speculations

### by Seiya Uyeda

The middle of the ocean is not its deepest part. Great depths are found in trenches at the margins of oceans. With the exception of the Indonesian, Antilles, and Scotia deeps, all of the major trenches are found in the Pacific Ocean (Figure 1). In a broad sense, even the three exceptions may be regarded as belonging to the Pacific margin. They form the belts of active volcanoes, the so-called [illegible] around the Pacific. World maps show that the margins also form belts of high seismicity (see page 64). These features are in sharp contrast with most of the margins of the Atlantic and Indian Oceans. Margins with trenches are termed active or of Pacific type, whereas margins without trenches are called passive or of Atlantic variety. Recent studies of both classifications have yielded a considerable amount of new information, leading to some new theories.

*Volcano Taal erupting in Luzon, Philippines. (Photo by Josephus Daniels, PR)*

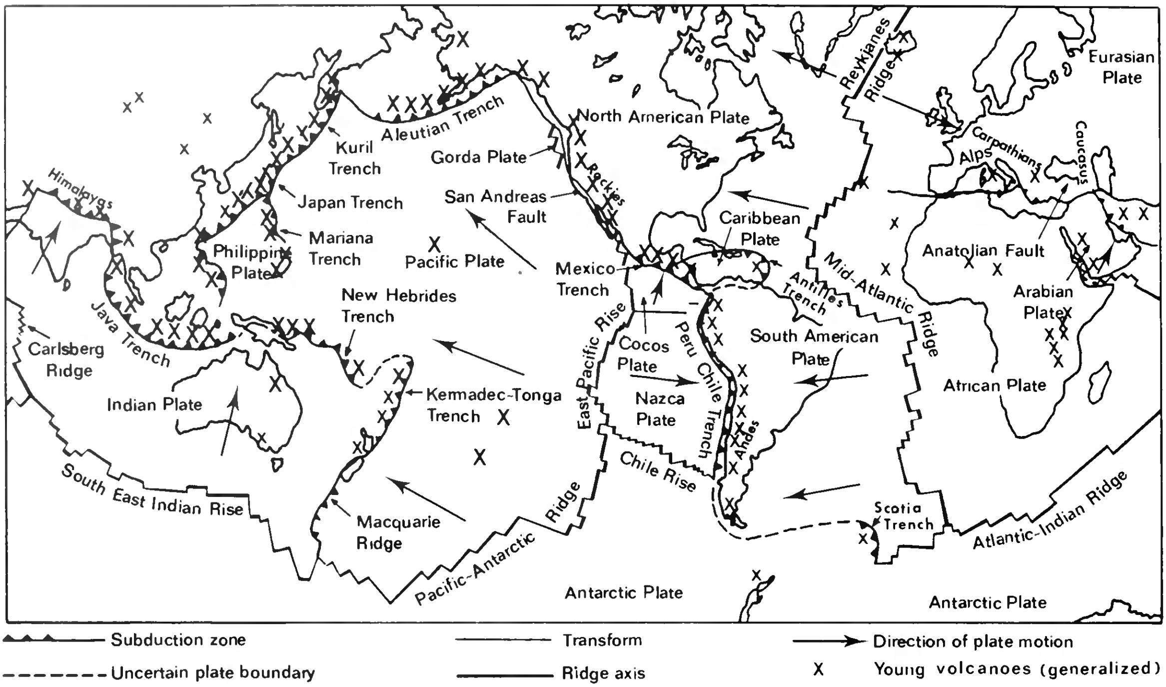


*Figure 1. Worldwide plate boundaries. The earth's lithosphere is broken into large rigid plates, each moving as a distinct unit. The relative motions of the plates, assuming the African plate to be stationary, are shown by the arrows. Plate boundaries are outlined by earthquake belts. Plates separate along the axes of mid-oceanic ridges, slide past each other along transform faults, and collide at subduction zones. (Adapted from J. F. Dewey, Plate Tectonics, Scientific American, 1972)*

It has been suspected for some time that the tectonic features at active margins are the result of a common basic process. Since the late 1920s, Arthur Holmes of the University of Edinburgh, Scotland, and others have suggested that the common process was a down-thrusting mantle convection current. Later, development of the theory of plate tectonics brought a sharper focus to the earlier concept, identifying the leading edge of the rigid oceanic plate as the material being thrust downward into the mantle.

The subduction or consumption of oceanic plates is a logical consequence of sea-floor spreading (see *Oceanus,* Vol. 17, No. 3). Because oceanic plates are continually being generated at mid-oceanic ridges, they have to be consumed somewhere to keep the earth's surface area constant. Active margins, with deep trenches and seismicity, were the most obvious localities. It is important to check this concept against the latest data from active margins. Can the process of subduction really explain the tectonic features at active margins?

The east-west geophysical cross section of the northeastern Japan arc at about 40 degrees North is shown in Figure 2. The topography is characterized by the deep Japan Trench and the island arc with its back-arc basin — the Sea of Japan (Figure 2a). The crustal structure corresponds well with the topography (Figure 2b). The island arc has a well developed continental crust, whereas the crust of the Sea of Japan is oceanic. This is common to all back-arc basins. The seismic wave velocity of the uppermost mantle (Pn velocity) under the arc is only 7.5 kilometers per second, which is abnormally low. This means that the uppermost mantle under the Japan arc is probably partially molten — that is, the lithosphere is as thin as the crust itself (about 30 kilometers). This is an anomalous situation, but seems to be in harmony with the heat flow distribution shown in Figure 2d. Heat flow is low on the Pacific Ocean side, but becomes high at about the position of the seaward front of the active volcanoes. It remains high in the entire Sea of Japan. Similar heat flow features have been found in other active margins. The inclined zone of seismicity in Figure 2e is the so-called Benioff-Wadati zone.* It was recently discovered that this zone under Japan has a double-layered structure. Whether the zones under other arcs also are double-layered has not yet been determined.

---

*It is often called the Benioff zone (named after Hugo Benioff at the California Institute of Technology) in western literature, but the author prefers to call it the Benioff-Wadati zone to give due credit to his fellow countryman who first noted the deep earthquakes in the 1930s.

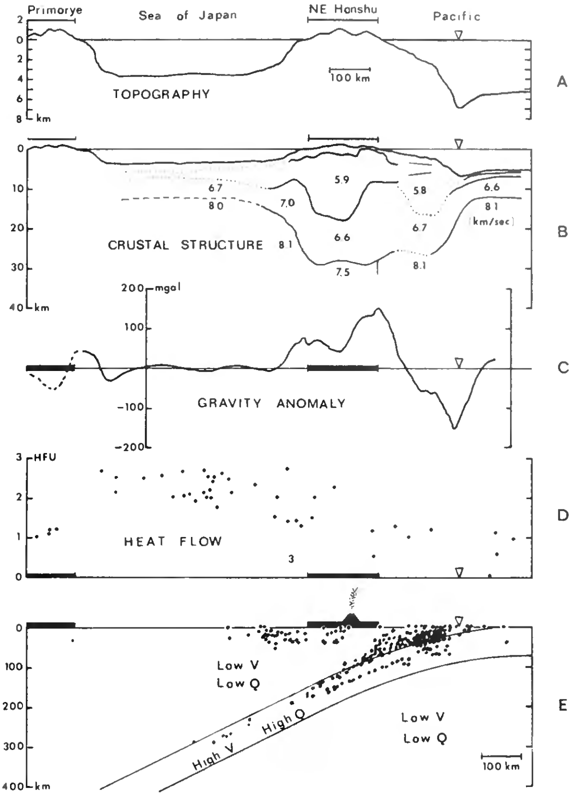


*Figure 2. The northeast Japan arc. In 2e, V and Q mean the velocity and quality factor of seismic waves, Low (High) Q means high (low) attentuation. (Adapted from Yoshii, 1979; Utsu, 1971; Hasegawa and others, 1978)*

As previously stated, the seismicity of the area generally fits the concept of subduction, although detailed accounts cannot be given here for the different kinds of earthquakes shown in Figure 2e. If we look at just one group of shocks, namely, the great shallow earthquakes at active margins, we find that nearly all are of the thrust-type (see page 66, Figure 3). These earthquakes are believed to be the direct results of the under-thrusting of the oceanic plate. The concept of a cold slab under the arc was strengthened when seismologists discovered that the inclined zone of the slab has a higher velocity and lower attenuation of seismic waves than the adjacent upper mantle (Figure 2e). In contrast to the slab, the wedge of the upper mantle above the slab has been shown to have low velocity and high attenuation of seismic waves. Moreover, the actual continuation of oceanic crust underneath the arc has been made visible by seismic reflection profiles at many active margins (Figure 3).

## Unsolved Problems

Are we then completely satisfied with the subduction hypothesis? No, not quite. There are still many important unsolved problems. One is the *thermal regime* of the subduction zones. How can we explain such features as the high heat flow in the back-arc basins, the low velocity and high attenuation anomalies of the mantle wedge, and the active arc volcanism? Because the down-thrusting slab is colder than the surrounding mantle, the subduction process is thermally akin to pouring ice water into hot water! Thus far there are two possible explanations. One group of scientists attributes the high heat flow to the friction between the mantle and the subducting slab (Figure 4a). Thus if the heat generated by the friction becomes high enough, its effect might, at least locally, overcome the cooling effect of the downward-thrusting slab to the extent that melting might occur. The melt would ascend to transfer the heat to the surface. The models of this kind, however, are plagued by the intrinsic weakness that appreciable frictional heat can be produced only when the mantle/slab interface can sustain high shear stress. If the temperature at the interface rises because of frictional heat, the material tends to become incapable of sustaining high stress. Thus the frictional heat model needs further examination.

The other group of scientists postulates that a secondary heat flow is induced in the upper mantle wedge by the subducting slab, and that this flow brings the hot lower material up (Figure 4b). Shear heating in the flow also would help to raise the temperature at the point where the flow is most concentrated. Thus an overturning of the mantle wedge, whether induced by subduction of the slab or some other process, appears to be a promising explanation for the high heat flow in the back-arc basins. It is, however, uncertain if this type of mechanism would account for arc volcanism.

The problem of magma production under the arcs is somewhat more complex. Petrological and geochemical studies of arc volcanics have not yet answered the question of whether magma generation involves melting of subducted ocean crust. If melting of subducted crust is not required, magma would be generated in the asthenospheric wedge above the slab. This is not impossible since the asthenospheric wedge is already hot, and the melting point would be lowered because of the water supply from the slab, resulting in the production of magma. Oceanic crust is believed to contain substantial amounts of water in the form of hydrous minerals. These minerals would release water through dehydration at depths close to 100 kilometers during subduction. If, on the other hand, geochemical data indicate melting of the cold slab, how it is heated would pose a real challenge to theoreticians.

It was stated previously that seismicity data fit well with the subduction model. However, this does not mean that all the mechanical aspects of active margin zones are free of problems. Just the opposite, there is a major problem — the *origin of back-arc basins*. It is now believed that they have been formed by extension. Just as the high temperature in the mantle wedge under the arcs is

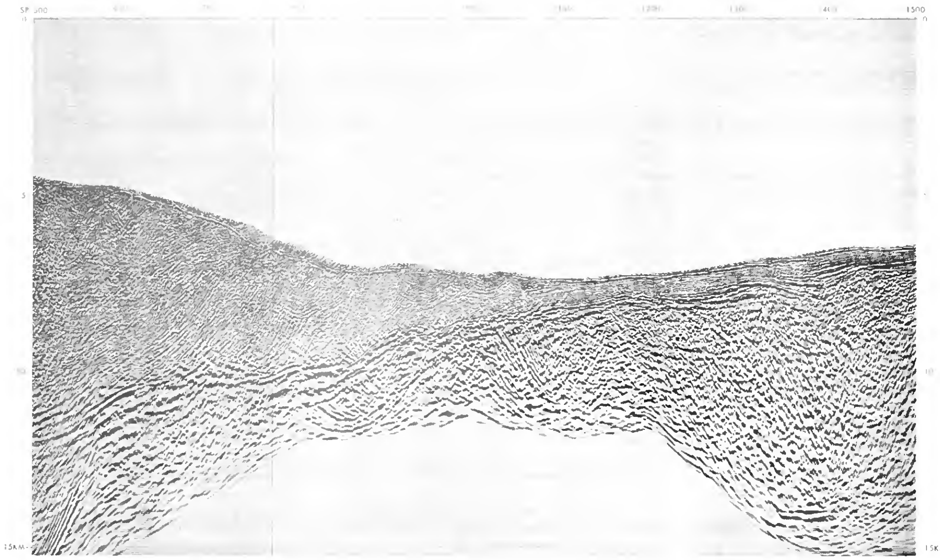


*Figure 3. Multi-channel profile across the Japan Trench. (IPOD – Japan Basic Data Series No. 3, 1979)*

not a natural expectation from the subduction of a cold slab, the extensional tectonics of the back-arc region are not what one would expect from an area where two plates are converging. A compressional tectonics is what would be expected.

How, then, does the back-arc region come under an extensional stress regime? Again, a great deal of effort has gone into solving this paradox. In general, three different models have been presented thus far, two of which correspond to the models for the thermal regime, indicating that the thermal and mechanical aspects go together. The first model attributes the opening of the back-arc basins to the ascent of large quantities of magma from below (Figure 4a), whereas the second model attributes it to the shearing stresses caused by the induced flow (Figure 4b). The third model calls for the oceanward retreat of trenches by a spontaneous collapse of the subducting plate. All the models were devised to support the concept of extensional tectonics above the subducting slab. Recently, however, the problem was looked at from a somewhat different perspective by several people, including this author.

### Two Modes of Subduction

It was first noticed that the extensional opening of a back-arc basin does not always accompany the subduction process. Specifically, not all subduction boundaries have back-arc basins; for example, the Peru-Chile arc does not have one. And active opening does not appear to be occurring in some of the arcs with back-arc basins. For instance, the Sea of Japan and Kuril Basin were probably formed by extension in the past, but there has been no opening activity in recent geologic time. In fact, there are relatively few back-arc basins that are considered to be actively spreading. They are the Mariana Trough, Lau Basin, Scotia Sea, Andaman Sea, and possibly the Okinawa Trough. Apparently, although subduction may be a necessary condition for back-arc spreading, it may not be the only one. It thus was surmised that even though there could be a built-in mechanism for generating a tensional stress in the back-arc region, as proposed by the models, actual back-arc spreading needs an additional enabling factor.

At this point, it became useful to break the subduction zones down into several groups, depending on the nature of their back-arc regions (Table 1). First, they were grouped into continental arcs and island arcs. By definition, the former arcs have no back-arc basins. Then, the island arcs were

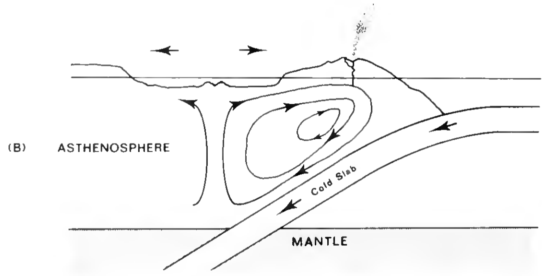


*Figure 4. Two views of the subduction zone thermal regime and back-arc spreading. (Not to scale)*

Table I. Classification of arcs.

| CLASSIFICATION | | | | STRESS REGIME | TYPICAL EXAMPLES |
|---|---|---|---|---|---|
| Arc | Continental arc (without back-arc basins) | | | Compressive (or neutral) | Peru-Chile, Alaska |
| | Island arc (with back-arc basin) | Back-arc inactive | Back-arc inactivated | Compressive (or neutral) | Kuril, Japan<br>Shikoku, Parece Vela Basins |
| | | | Back-arc trapped | Compressive (or neutral) | Bering Sea |
| | | Back-arc active | Back-arc spreading | Tensional | Mariana Trough,<br>Scotia Sea,<br>Lau Basin |
| | | | Leaky transform | Tensional with shear | Andaman Sea |

grouped into those having inactive back-arc basins and active back-arc basins, with each of them further divided into sub-groups according to the possible origin of the back-arc formation. Of course, such a classification is too idealized; there are arcs of an intermediate or hybrid nature. As indicated in Table 1, the arcs with active back-arc basins are suspected of being tensional. The author and a colleague examined this point with the aid of published focal mechanism solutions to intra-plate earthquakes occurring in back-arc regions, demonstrating that present-day stress regimes are in accord with expectations. We also noticed that there was a significant difference between the inter-plate thrust-type earthquakes in the two groups of subduction zones. Although all subduction zones are almost equally populated by the black dots in Figure 1 of Donovan's article (see page 64), therefore appearing equally seismic, the energy released by earthquakes is in fact almost two orders of magnitude different in the two groups of subduction zones. More than 90 percent of global seismic energy is released in subduction zones *without* active back-arc basins. Earthquakes significantly greater than 8.0 on the new magnitude scale, Mw,* have occurred almost exclusively at the subduction zones *without* active back-arc basins (Figure 5).

From these and other considerations, it now appears that there are two different basic modes of subduction as depicted in Figure 6. In one, called the Chilean-type, subduction proceeds with a strong interaction between the two converging plates, whereas in the other, called the Mariana-type, the oceanic plate subducts without exerting any strong compressive stress to the landward plate. This basic difference may be one of the principal causes of the various differences in the tectonics of the subduction zones. The effect of different modes of subduction may indeed be far reaching, causing significant differences in the types of arc volcanism and metallogeny — for example, the calc-alkaline volcanism versus the basalt-rhyolite bimodal volcanism, and the porphyry copper deposits versus the Kuroko-type massive sulfide deposits.

Another important aspect of the mode of subduction is its possible relevance to the tectonics of the *fore-arc* region. It has been generally recognized that fore-arc regions are characterized by basins and the mid-slope structural high that dams the basin sediments from the arc. The structural high has been interpreted as being the result of a raised subduction complex that consists presumably of pelagic sediments, trench sediments, and fragments of ocean crust (ophiolites — see page 23). The subduction complex is considered to have been accreted after having been scraped off the under-thrusting plate and raised by horizontal compression caused by continuous understuffing. As can be seen in Figure 6, there may be differences in the degree of development of such structural highs and the fore-arc basins in the subduction zones of different modes; namely, the development of these features would be more effective for the Chilean-type subduction than for the Mariana-type. This supposition is supported by the observation that the prominent structural highs are more common in the Chilean-type subduction, namely the Peru-Chile, Alaska, and Sumatra arcs, whereas in the Mariana and Tonga arcs, the trench

---

*This new magnitude scale was introduced by Kanamori in 1978 to correctly scale great earthquakes, the Richter scale suffering from saturation beyond magnitude greater than 8 (see page 63).

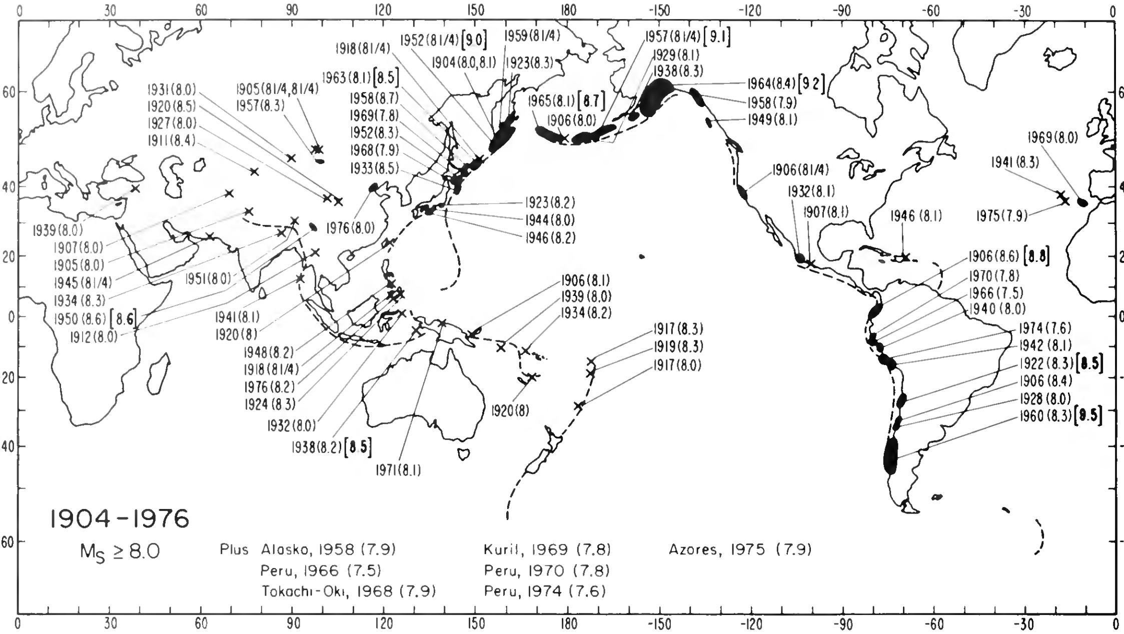


*Figure 5. Great earthquakes from 1904 to 1976. Conventional magnitudes are in parentheses, and new magnitudes are in brackets. Black areas are rupture zones. (After Kanamori,* Nature, *1978)*

walls are devoid of sediments. In fact, Leg 60 of the Deep Sea Drilling Project (DSDP — See *Oceanus*, Vol. 21, No. 3) found no ocean-derived sediments on the fore-arc of the Marianas. It may even be possible that some tectonic erosion (upper plate subduction) is in progress in the Mariana-type subduction zones. Leg 56 and 57 of the DSDP drilled the fore-arc region of the Japan Trench, failing to reach any accreted pelagic sediments. If understuffing is taking place, it must be going on below the drilled holes (Figure 7). This finding dealt a serious blow to the scraping-off hypothesis, which clearly needs reconsideration. In this regard, however, it should be pointed out that the northeast Japan arc is now a Chilean-type, but has been so for only a relatively brief geological period. If we take about 40 million years ago as the beginning of the present phase of subduction at the northeast Japan arc, there is some indication that the subduction remained the Mariana-type until several million years ago. The Sea of Japan might have been formed during this period of Mariana-type subduction. The relatively short period of time, then, for Chilean-type subduction could account for the difficulty in encountering the accreted pelagic sediments. This is a very speculative view, which needs testing by further drilling at many other fore-arc regions.

## Two Subduction Modes: Causes and Consequences

If two modes of subduction exist, then the next question is: what is the cause of such a distinction? There appears to be three possible models:

***Model 1:*** *The different modes of subduction represent different stages of a single evolutionary process. The subduction initially starts with the Chilean-type mode, and, as the process continues, the mechanical coupling of the two plates weakens, with the mode evolving into the Mariana-type. The slab in the Mariana-type subduction finally becomes detached, enabling a new subduction to start in the Chilean-type mode again.*

***Model 2:*** *The age of the subducting plate, to some extent, controls the mode. When the subducting plate is young, such as the Nazca Plate, the Chilean-type mode occurs because it is not cold and dense enough, whereas the older Pacific plate subducts in the Mariana-type mode because it is cold and dense.*

***Model 3:*** *The motion of the landward plate controls the mode. When the slab goes deep into the mantle, the position of the trench tends to be anchored to the deep mantle. Therefore, when the landward plate moves away from the trench, as with the Philippine Sea plate, the Mariana-type mode of subduction occurs, whereas when the landward plate advances toward the trench, as with the South American plate, the mode is Chilean-type.*

Model 1 appears plausible as an explanation, but to be accepted it must be verified that such a cycle really has taken place at various active margins in the geological past. Model 2 explains present-day observations (Figure 8), and appears to be physically sound, too. However, if this was the sole cause, it does not explain why the Sea of Japan has stopped spreading. Model 3 appears to be supported by the system of the absolute motions of plates (Figure 9).

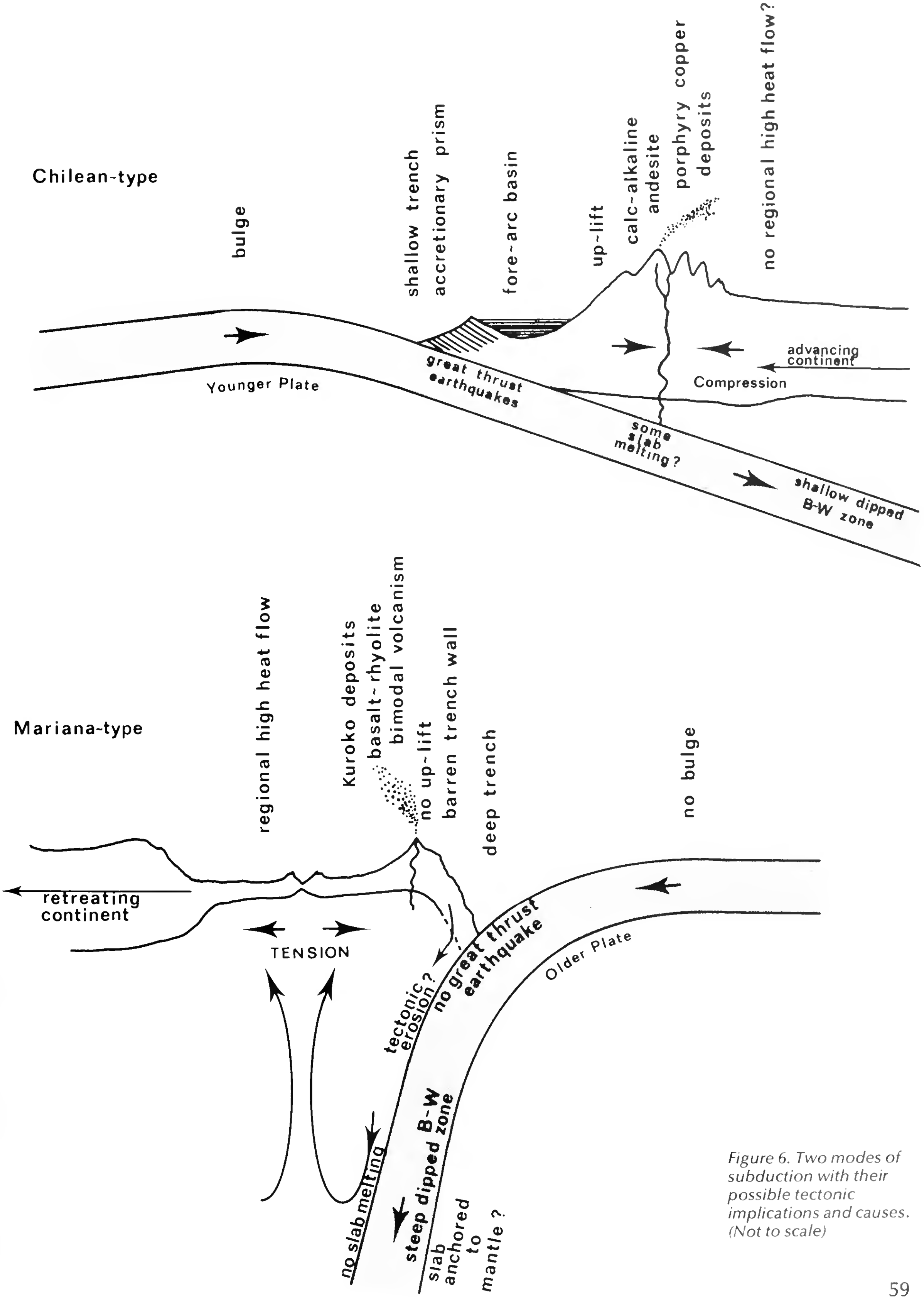


*Figure 6. Two modes of subduction with their possible tectonic implications and causes. (Not to scale)*

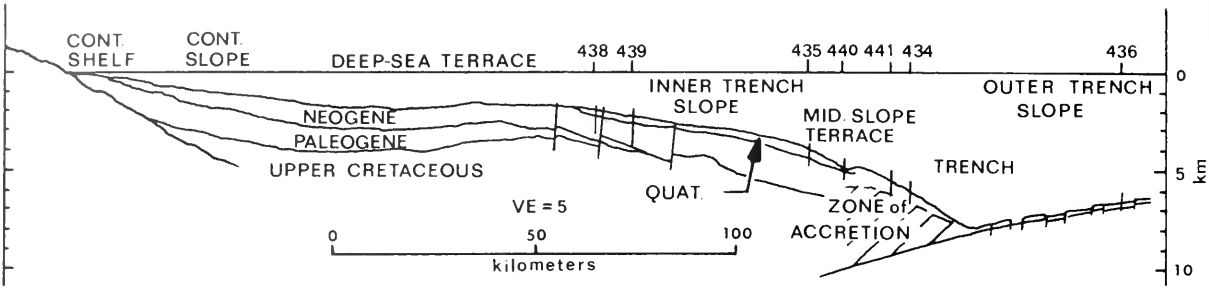


*Figure 7. Drill site locations for Legs 56 and 57 of the Deep Sea Drilling Project. (After R. von Huene and others, Geotimes, 1978)*

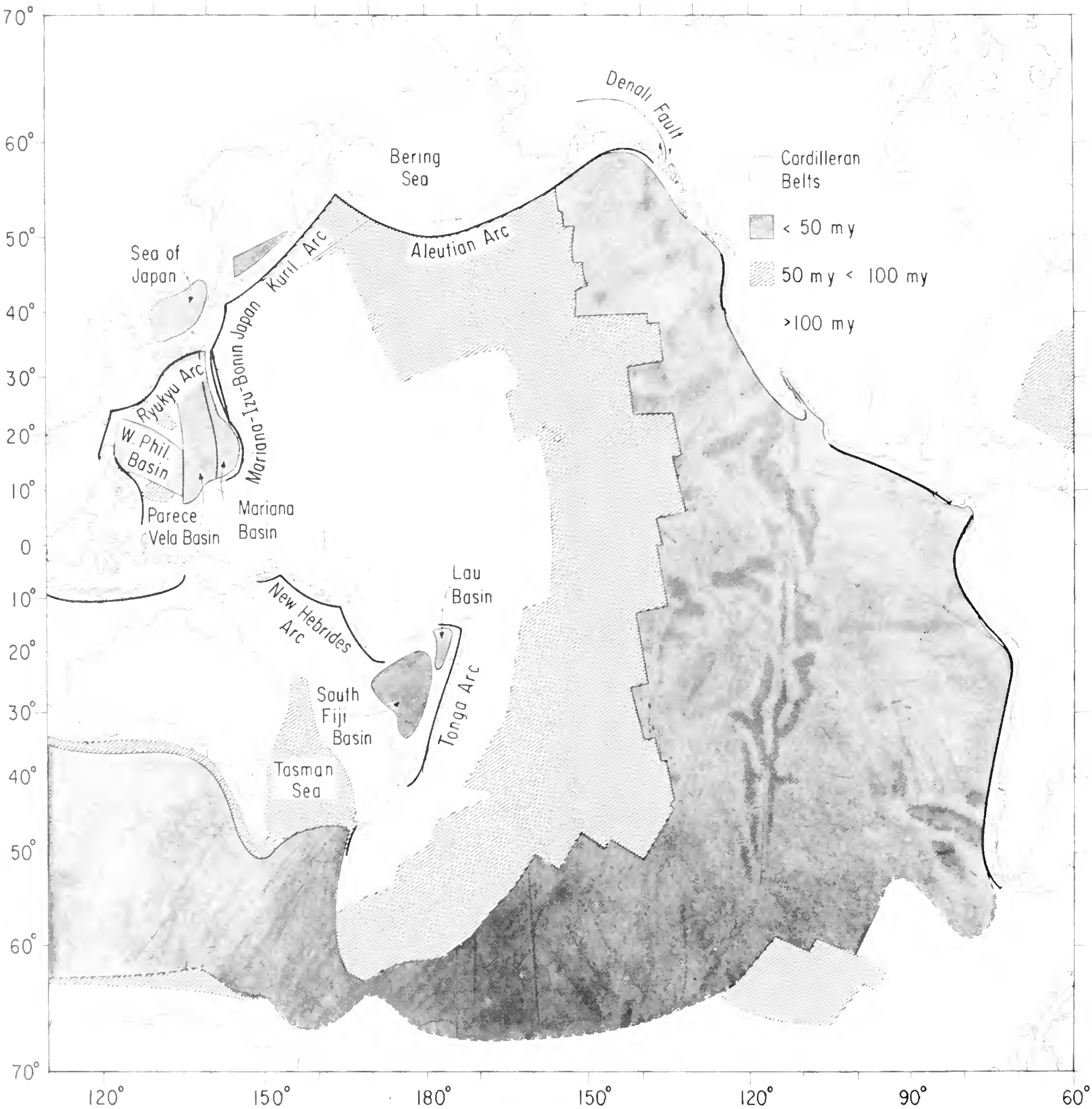


*Figure 8. The age of the ocean floor in Pacific area. (After Molnar and Atwater,* Earth and Planetary Science Letters, *1978)*

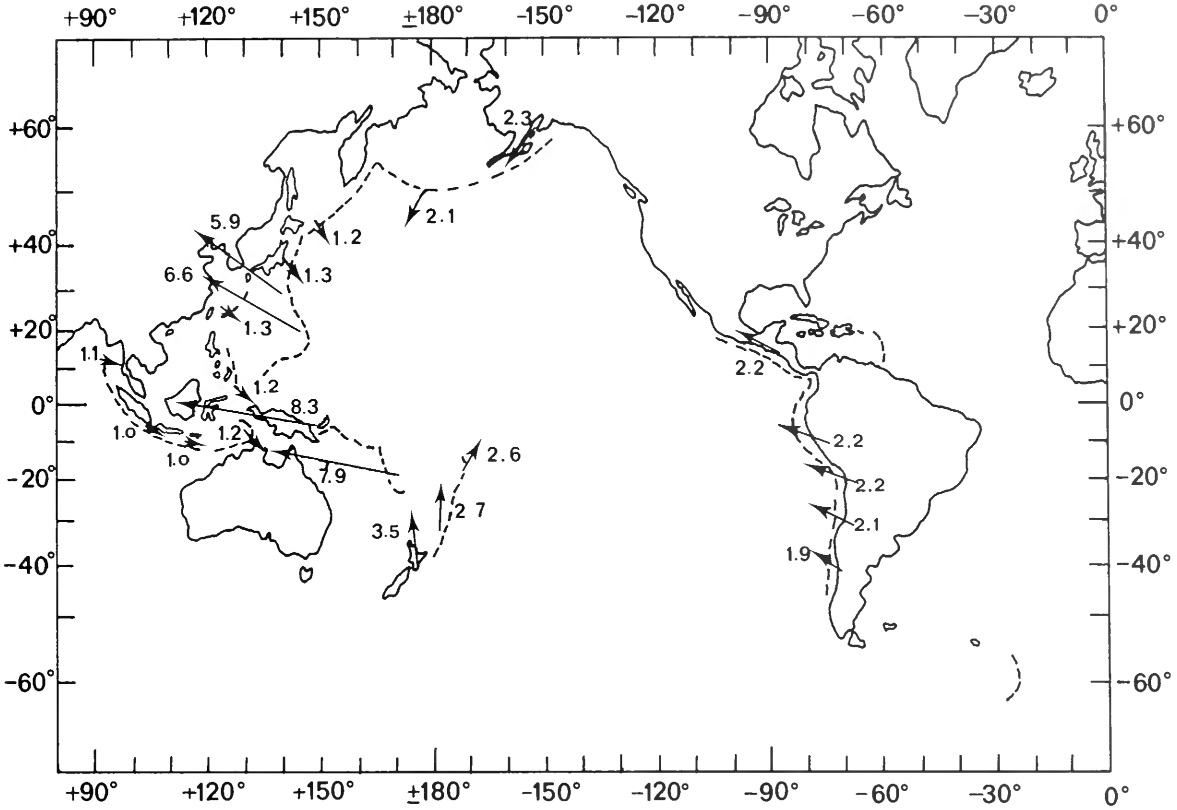


*Figure 9. Upper plate velocities in Pacific area.*

At present, it seems premature to decide which of the above models is closest to reality.

What appears to be common in the models is that back-arc basin spreading is a passive process — just like ocean-floor spreading at mid-oceanic ridges. Therefore, except for the subducting slab, the upper mantle process for back-arc spreading is similar to regular sea-floor spreading. In fact, the similarity in both types of spreading can be noted in the magnetic lineation patterns, high heat flow, and the nature of basement rocks.

Of course, there are dissimilarities, too. For example, magnetic lineations are often considerably less intense and regular in the back-arc basins than in the ocean floor. But such a dissimilarity may be of secondary importance. With regard to heat flow, recent data indicate that hydrothermal activity similar to that at mid-oceanic ridges is occurring in the Mariana Trough, an active back-arc basin. There is, therefore, a distinct possibility that the high heat flow in the back-arc basin may be explained by the passive upwelling of asthenospheric material, similar to the process of plate accretion at mid-oceanic ridges.

The thermal activity for arc volcanism may have an origin somewhat different from that of the regional high heat flow, because arc volcanism exists in both the Mariana-type and Chilean-type arcs. In fact, even in the Mariana-type arcs, the sites of the back-arc spreading axis and the volcanic arc are far apart, producing different types of rocks. Arc volcanics appears definitely to be *directly* related to the subducting slab. In this regard, it is important to note that recent geochemical studies on isotopes and trace elements suggest that volcanics in the Aleutian, Caribbean, Japan, East Java, and South American arcs may require the melting of a subducted slab, whereas those in the Tonga and Mariana arcs do not. If this is indeed the case, it is understandable why geochemists never arrive at unanimous conclusions about the melting of the slab. What is interesting to the author is that this distinction again falls into the Chilean and Mariana types of subduction zones. It is tempting to assume that the difference in the strength of inter-plate mechanical coupling between the two types of subduction modes results in the different geochemistry of the volcanics. Stated another way, it may be hypothesized that in the Mariana-type subduction zones frictional heat is minimal, with arc magma generated in the mantle wedge and thus back-arc spreading causing the regionally high heat flow. In the Chilean-type subduction zones, arc volcanism involves some melting of the slab by strong friction, but there is no sea-floor spreading-type high heat flow in the back-arc area.

*Seiya Uyeda is Professor of Geophysics at the Earthquake Research Institute, University of Tokyo, Japan, and currently a Visiting Professor in the Department of Earth and Planetary Sciences at the Massachusetts Institute of Technology.*

### Selected Readings

Andrews, D. J., and N. H. Sleep. 1974. Numerical modelling of tectonic flow behind island arcs. *Geophys. J. Roy. Astron. Soc.* 38: 237-51.

Barazangi, M., W. Pennington, and B. Isacks. 1975. Global study of seismic wave attenuation in the upper mantle behind island arcs using P-waves. *J. Geophys. Res.* 80: 1079-92.

Chase, C. 1978. Extension behind island arcs and motions relative to hot spots. *J. Geophys. Res.* 83: 5385-87.

Elsasser, W. M. 1971. Sea-floor spreading as thermal convection. *J. Geophys. Res.* 76: 1101-12.

Hasebe, K., N. Fujii, and S. Uyeda. 1970. Thermal processes under island arcs. *Tectonophys.* 10: 335-55.

Hasegawa, A., N. Umino, and A. Takagi. 1978. Double-planed deep seismic zone and upper-mantle structure in the northeastern Japan Arc. *Geophys. J. Roy. Astron. Soc.* 54: 281-96.

Hobart, M. A., R. N. Anderson, and S. Uyeda. 1979. Heat transfer in the Mariana Trough. *EOS* 60: 383.

Hussong, D., S. Uyeda, and Scientific Party of DSDP, Leg 60. 1978. *Geotimes*, Oct. 1978, pp. 19-22.

Kanamori, H. 1971. Great earthquakes at island arcs and the lithosphere. *Tectonophys.* 12: 187-98.

———. 1977. The energy release in great earthquakes. *J. Geophys. Res.* 82: 2981-87.

Karig, D. E. 1971. Origin and development of the marginal basins in the western Pacific. *J. Geophys. Res.* 76: 2542-61.

Minster, J. B., H. Jordan, P. Molnar, and E. Haines. 1974. Numerical modeling of instantaneous plate tectonics. *Geophys. J. Roy. Astron. Soc.* 36: 541-76.

Moberly, R. 1972. Origin of lithosphere behind island arcs, with reference to the western Pacific. *Geol. Soc. Amer. Mem.* 132: 35-55.

Molnar, P., and T. Atwater. 1978. Interarc spreading and cordilleran tectonics as alternates related to the age of subducted oceanic lithosphere. *Earth Planet. Sci. Lett.* 41: 330-40.

Scholtz, C. H., M. Barazangi, and M. Sbar. 1971. Late Cenozoic evolution of the Great Basin, western United States, as an ensialic inter-arc basin. *Geol. Soc. Amer. Bull.* 82: 2979-90.

Seely, D. R. 1978. The evolution of structural highs bordering major forearc basins. *Amer. Assoc. Petrol. Geol. Memoir* 29: 245-60.

Sleep, N., and M. N. Toksoz. 1973. Evolution of marginal basins. *Nature* 233: 548-50.

Takeuchi, A., K. Nakamura, Y. Kobayashi, and K. Hori. 1979. Restoration of tectonic stress field of Cenozoic central Honshu. *The Earth Monthly* 1, Symposium 6: 447-52.

Utsu, T. 1971. Seismological evidence for anomalous structure of island arcs with special reference to the Japanese region. *Rev. Geophys. Space Phys.* 9: 839-90.

Uyeda, S. 1978. *The new view of the Earth — moving continents and moving oceans.* San Francisco: W. H. Freeman and Co.

Uyeda, S., and H. Kanamori. 1979. Back-arc opening and the mode of subduction. *J. Geophys. Res.* 84: 1049-61.

von Huene, R., N. Nasu, and Scientific Party of DSDP, Leg 57. 1978. *Geotimes*, April, 1978, pp. 16-20.

Yoshii, T. 1979. A detailed cross-section of the deep seismic zone beneath northeastern Honshu, Japan. *Tectonophys.* 55: 349-60.

## Attention Teachers!

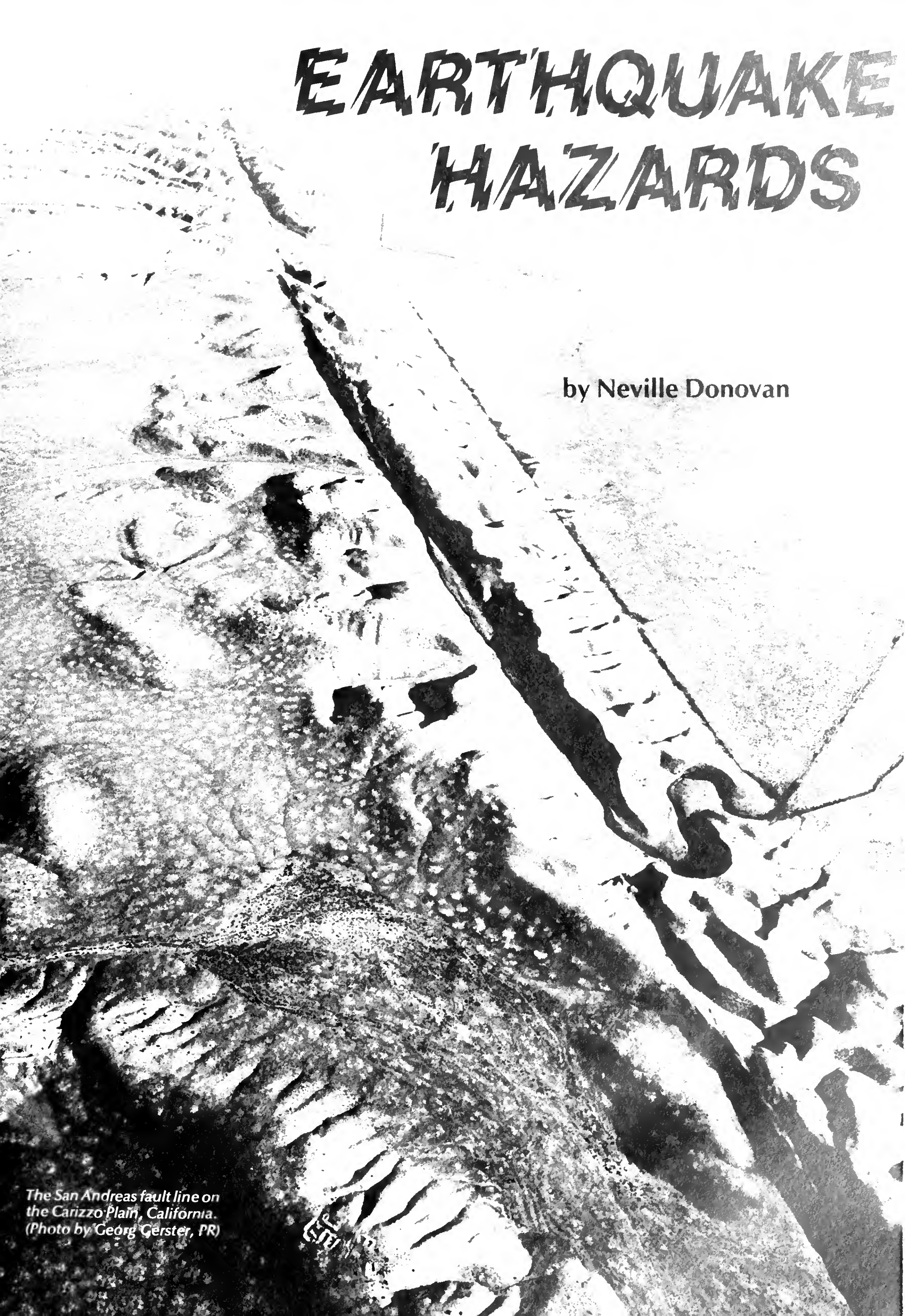
We offer a 40 percent discount on bulk orders of five or more copies of each current issue — or only $1.65 a copy. The same discount applies to one-year subscriptions for class adoption ($6 per subscription). Teachers' orders should be sent to our editorial office (see address at right), accompanied by a check payable to Woods Hole Oceanographic Institution.

## Hot Sketch Wanted

Is there an Al Capp of marine science out there? *Oceanus* is searching for a scientist with a sense of humor — pure or applied — who can also draw. If you're a hot sketch or think you could produce some, send your cartoons to: The Editor, Oceanus, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543.

# EARTHQUAKE HAZARDS

by Neville Donovan



*The San Andreas fault line on the Carizzo Plain, California. (Photo by Georg Gerster, PR)*

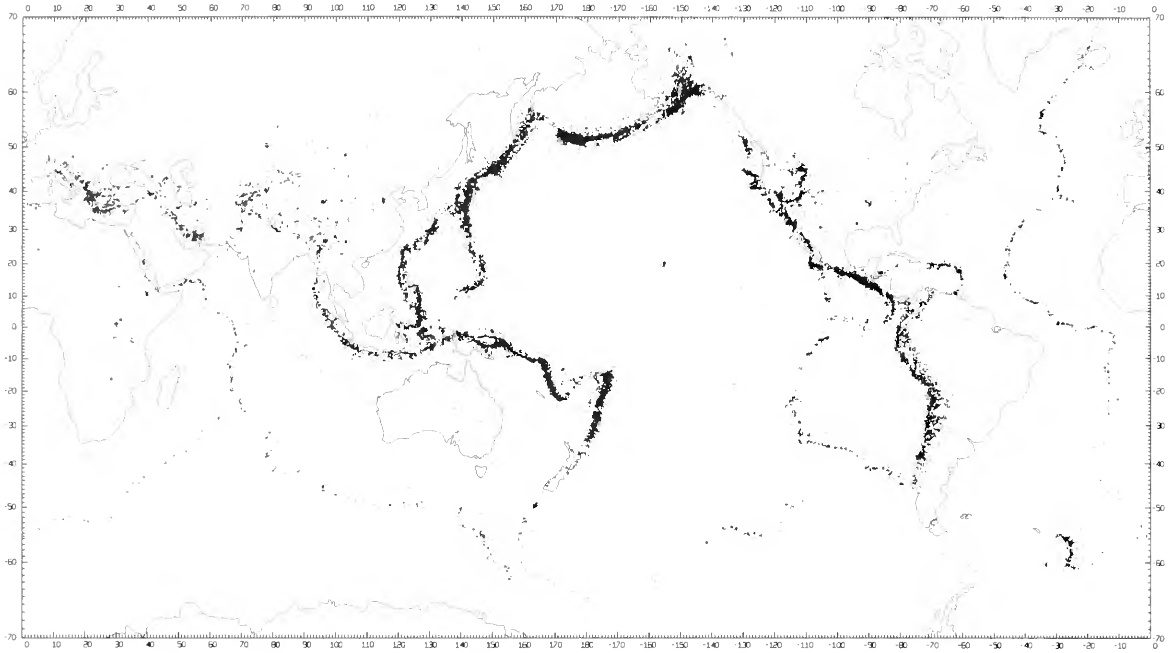


*Figure 1. Distribution of earthquake epicenters with focal depths of less than 100 kilometers (1961-1967). Note location of mid-oceanic ridges and continental margins. (From Barazangi and Donovan, BSSA, 1969)*

Our understanding of global tectonics and mountain-building processes has increased rapidly since the continental drift theory advanced by Alfred Wegener in 1915. Seismologists began to examine earthquakes on a global basis when it was recognized that regional features and occurrences had to be looked at as part of a global phenomenon. The World Wide Seismic Network (WWSN) was established in the early 1960s, and by 1969 a consistent set of seismic events with body-wave magnitudes of 4.5 or greater had been compiled. Also that year, Muawia Barazangi and James Dorman of the Lamont-Doherty Geological Observatory at Columbia University published world seismicity maps based on data for the period 1961 to 1967. One of their maps, showing the epicenters* of shallow earthquakes with focal depths of less than 70 kilometers, is shown in Figure 1. Although the major seismic regions of the earth already had been documented, the precise location of small earthquakes along such features as the mid-oceanic ridges had not been recognized. For example, the location of the Mid-Atlantic Ridge can be accurately inferred from the seismic data in Figure 1.

This figure also shows that the major concentrations of shallow earthquakes are associated with continental margins. Earthquakes, mountain scenery, ocean trenches, and volcanic arcs are all consequences of the collision of plates, the major mountain-building or orogenic process.

The relationship between continental margins and earthquakes is even more clearly shown by plotting the distribution of epicenters deeper than 100 kilometers (Figure 2). With the exception of Northern Pakistan (related to the collision of the Indian and Asian tectonic plates), the deep activity is concentrated around the Pacific basin. It is in the areas around the Pacific basin — associated with the major trenches, such as the Peru-Chile Trench, the Kermadec Trench, the Japan Trench, and the Aleutian Trench — that 90 percent of the world's seismic energy is released.

Earthquakes occur when accumulated stresses in rock (produced by progressive, slow strain) are released by slippage along a fault. The fault movement can be of several types, or a combination of basic types (Figure 3). For example, the fault rupture in the 1971 San Fernando earthquake in Southern California was along a reverse or thrust fault, whereas movements on the San Andreas fault are of the strike-slip type in the right lateral sense (when standing on one side of the fault while facing it, the opposite side moves to the right).

---

*Points on the surface of the earth beneath which fault ruptures during earthquakes are believed to start.

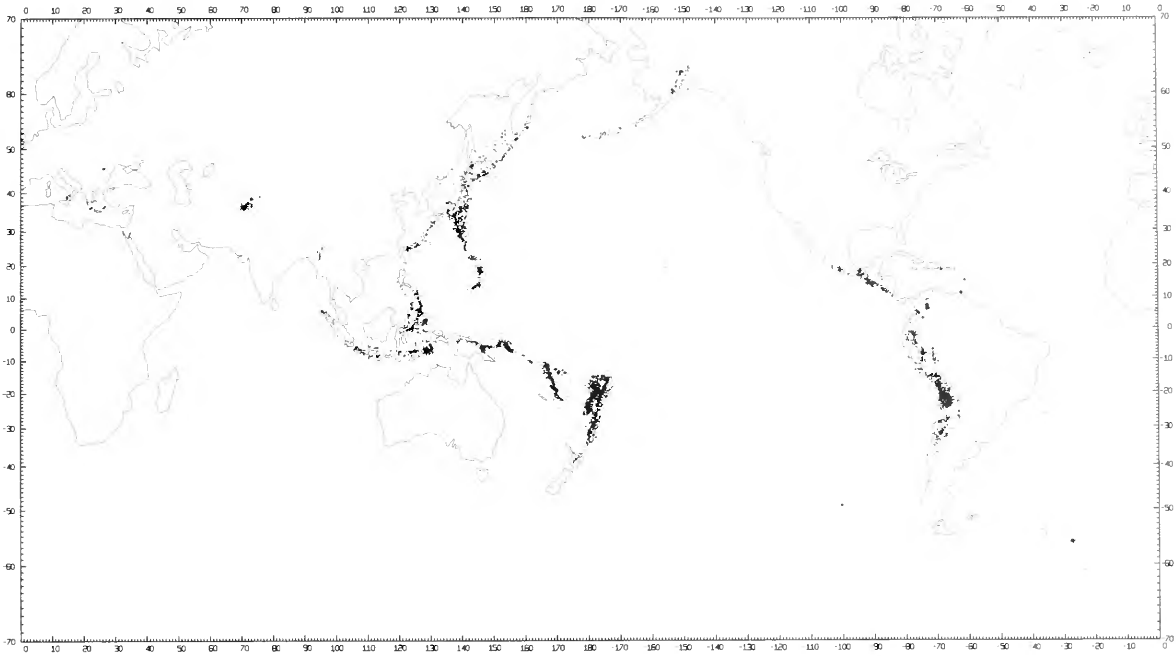


*Figure 2. Distribution of earthquake epicenters with focal depths greater than 100 kilometers (1961-1967). Deep-focus earthquakes only occur at the continental margins, which are major subduction or collision zones. (From Barazangi and Donovan, BSSA, 1969)*

The size of earthquakes can be measured by several different scales. On the Modified Mercalli scale (MMI), the intensity of an earthquake is judged according to the observed effects. It is expressed in Roman numerals, beginning with I, barely felt by experienced observers, and runs to XII, representing total destruction. These data can be interpreted from old documents and are the only records available historically. Beno Gutenberg and Charles Richter of the California Institute of Technology devised another method — a magnitude scale, which is based on the logarithm of the maximum amplitude of the displacement trace on a standard instrument. Their original intention was to roughly separate large, medium, and small shocks in Southern California. The original value (designated $M_L$ and called the local magnitude) is different from that computed for distance events by the WWSN. The WWSN value is called a body-wave magnitude, or $m_b$. These different magnitude scales have created considerable confusion and have been hotly debated by seismologists for many years.

Large earthquakes are associated with fault ruptures several hundred kilometers in length. The seismograph records of large events, therefore, have longer durations than a smaller, close-by event. It has been observed that the maximum amplitude (used to compute the magnitude) reaches a boundary or "saturation" value, becoming inaccurate for large earthquakes.

In an attempt to provide a more meaningful and precise measure of earthquake size, many seismologists are using a newer quantity called the seismic moment. This represents the product of the change in volumetric strain energy (the change in stress or stress drop multiplied by the rigidity), the size of the fault rupture surface, and the actual displacement or throw of the fault. The seismic moment expressed in fundamental physical units becomes an incomprehensively large number. For example, the seismic moment of the 1971 San Fernando earthquake ($M_L$=6.5) was 1.4 x $10^{26}$ ergs. Research using a magnitude scale based on seismic moment, developed by Hiroo Kanamori of the California Institute of Technology, has suggested revisions in the relative sizes of some historic earthquakes. The 1906 San Francisco earthquake would be reduced, while the 1960 Chilean earthquake, which is probably the largest event in this century, would be increased.* Although

---

*Kanamori first compared the estimated energy release with the magnitude of moderate-sized events. The extrapolation was then made to large events by taking the Gutenberg-Richter relationship between magnitude and energy, and using the energy release computed from the seismic moment. It should be noted that while the new scale provides a better measure of the relative size of events, the recorded magnitudes of events using the $M_s$, $m_b$ and $M_L$ scales remain unchanged.

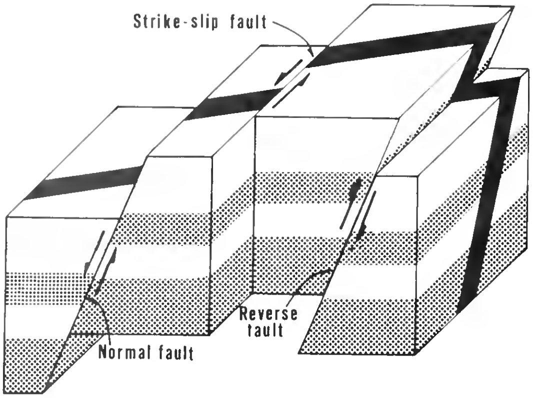


*Figure 3. The three most important types of fault motion. (From* Earthquakes: A Primer, *by Bruce A. Bolt, W. H. Freeman and Co. © 1978)*

seismic moment is more useful for the study of earthquakes, the complications brought about by the need to estimate three parameters have so far prevented the use of this quantity in the designing of structures to resist future earthquakes.

The specification of earthquake motion levels for design is usually made on the basis of an acceleration value expressed as either a decimal value or a percentage of g, the gravitational coefficient. As more data have been accumulated, it has been found that the peak acceleration value is an extremely poor way to describe an earthquake. For example, Tom Hanks and Dennis Johnson of the U.S. Geological Survey at Menlo Park, California, have shown that the peak acceleration on exposed surface rock close to the center of an earthquake is almost independent of magnitude above a threshold value of about $M_L$ equal to 4.5. Other quantities — such as velocity, displacement, and duration — can be associated with averages of peak acceleration to describe the most probable values that will be recorded in a future event, but this requires an acceptance of probabilistic methods. Using probabilistic methods in considering design requirements developed from risk studies immediately produces difficult decisions, such as determining the acceptable level of risk. This is a difficult task in any area, but becomes especially important in the context of ocean/continent margins. Sensitive facilities can be found along coastlines, such as nuclear power plants, offshore oil drilling platforms, and liquefied natural gas tanks. Although the hazards resulting from a potential accident at the various facilities are different, there are many people who argue that even a very small probability of an earthquake occurring larger than a design event is unacceptable. Thus, although the concept of zero risk is a desirable aim, it is also an impossible one.

A recent project aimed at improving seismic design criteria for buildings in the United States resulted in the development of probability-based zoning maps that show contours representing levels of Effective Peak Acceleration* (Figure 4). As a result of these maps, places that have experienced earthquakes only rarely, such as Boston in 1755 and Charleston in 1886, are now recognized as having lower risk levels than coastal California.

Strong ground motions are usually recorded on accelerographs. These instruments are triggered by the first motions of the earthquake, and then continue recording until some predetermined time, usually about 30 seconds after the motion ceases. Strong-motion instruments usually measure three components of acceleration — two horizontal, and one vertical. Figure 5 shows one of the horizontal components recorded in Golden Gate Park during the March 22, 1957, earthquake in San Francisco, a moderate event with an $M_L$ of 5.3 that occurred on the San Andreas fault. This record was made at a distance of approximately 11 kilometers from the fault. It is of shorter duration than records made by larger, or more distant events. Direct examination of a record does not provide much information on either the distribution of energy among the wide range of frequencies or on the probable types of wave motion present. For the physicist, a Fourier Spectra, which decomposes the recorded motion into a suite of sinusoids, or the Power Spectral Density Function, which directly shows the distribution of energy present among the different frequencies, would be the way to demonstrate this. The engineering fraternity has developed a similar, but different technique, using the response spectrum. Figure 6 is computed from the record in Figure 5 for two different levels of damping.

At first sight, Figure 6, with its tripartite form containing many axes, is much more confusing than informative. Because of the cyclic nature of seismic response, a 45-degree rotation of the axis allows direct scaling to the left and right of the response acceleration and displacement, plus the relative velocity scale shown on the vertical axis.

Using structural design methods, it is possible to directly incorporate either the computed response spectrum or the acceleration time history. In its most straightforward application, a structural framework is first developed by designers, who rely on their experience with similar structures. During the design earthquake, stresses and displacements that develop in parts of the structure — such as in columns and beams — are computed so that adjustments can be made to keep

---

*Effective Peak Acceleration (EPA) is a modification of the peak-recorded instrumental acceleration designed to represent the energy content in the ground motion to which buildings respond. Although the estimate is somewhat more complex, it can be likened to the filtering out of high-frequency spikes of acceleration which structures do not react to because of their considerable inertia.

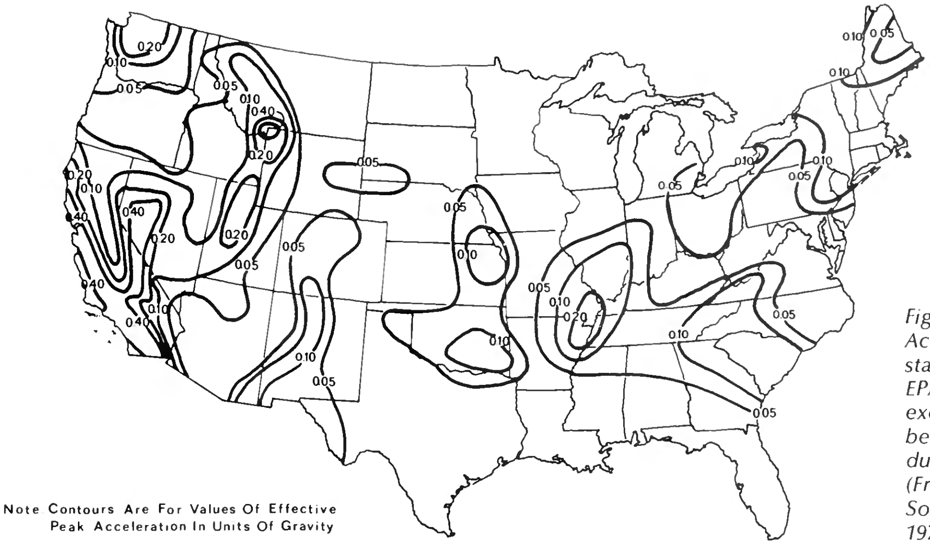


*Figure 4. Effective Peak Acceleration (EPA) for 48 states. Contours represent EPA levels with a non-exceedance probability of between 80 and 95 percent during a 50-year period. (From the American Society of Civil Engineers, 1978)*

them within acceptable limits. Design codes, specifying such limits, are the result of an understanding of engineering materials and their performance in different types of structures during actual earthquakes.

Most strong-motion earthquake data have been accumulated from events in California and Japan. When more strong-motion accelerographs are installed, the geographic coverage will improve and regional differences will become more apparent. California and Japan represent two different tectonic regions. The west coast of the United States is not typical of continental margins. The primary seismic feature is the well-known San Andreas fault, with its right lateral strike-slip movement (known as a transform fault, which is usually associated with mid-oceanic spreading ridges where it is of much shorter length and a consequence of the actual three-dimensional nature of the plates moving on the surface of the earth). As Figure 7 shows, the San Andreas fault joins the spreading East Pacific Rise and the spreading zones of the Gorda and Juan de Fuca ridges to the north. The realization that the fault was of a transform type was first made by J. Tuzo Wilson of the University of Toronto, Canada. He recognized that a fault displacement of up to 1,000 kilometers required some mechanism that allowed the displacements to occur while satisfying the laws for the conservation of matter. Because of the special nature of the relative movements between

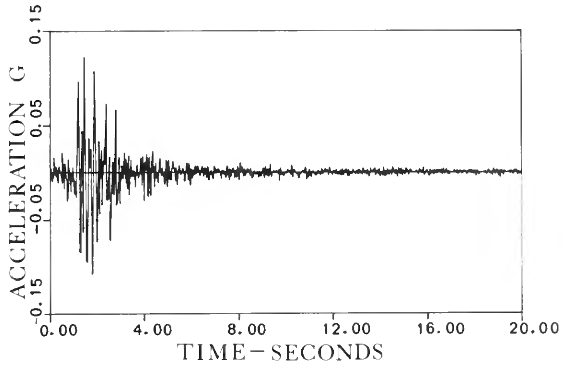


*Figure 5. Acceleration time history (Northeast component of accelerograph record obtained in Golden Gate Park, San Francisco, on March 22, 1957).*

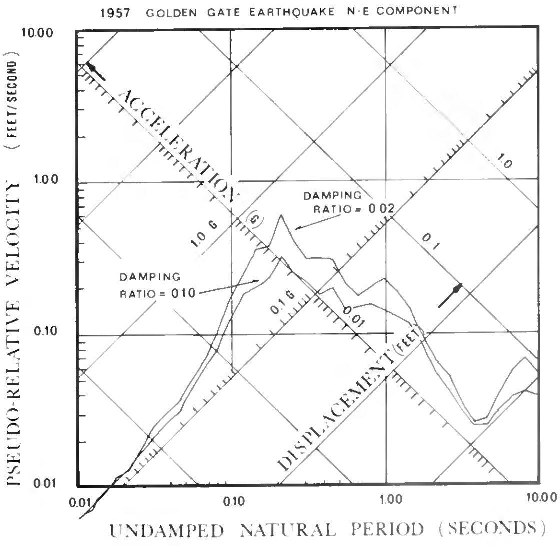


*Figure 6. Response Spectra computed from the record in Figure 5 for two levels of damping. The maximum response of any structure whose natural period of vibration is within the range shown on the horizontal scale of period can be read from scales for acceleration, velocity, and displacement.*

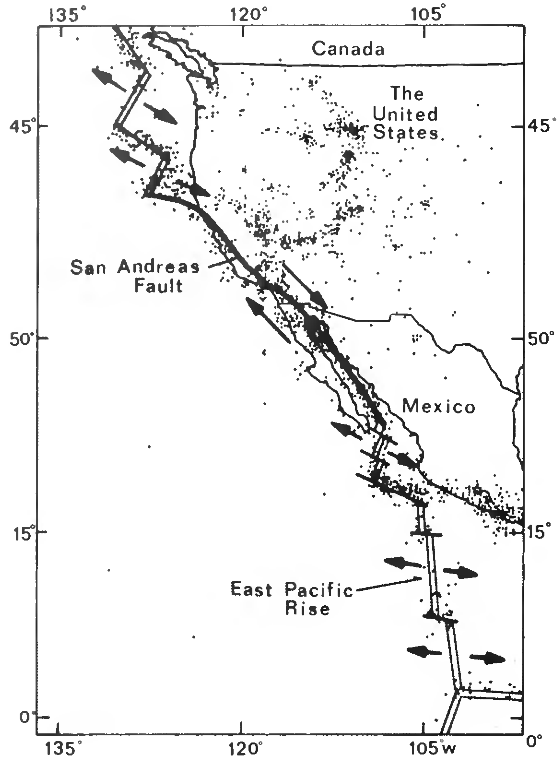


*Figure 7. The San Andreas fault as a transform fault. The shorter arrows show the movement of blocks away from each other. The long arrows show the movement of the two sides of the fault past each other. Dots represent earthquake epicenters. (From* The New View of the Earth, *by Seiya Uyeda, W. H. Freeman and Co.,* © *1978)*

the Pacific Plate and the North American Plates, the San Andreas fault may be thought of as a roughly landward excursion and a very large example of a mid-oceanic feature.

Most of the continental margin seismic activity is associated with direct plate collisions in areas where active subduction is occurring (see page 52). A typical place where this type of activity occurs is along the coast of Chile, where the focal depths of earthquakes increase eastward from the Peru-Chile trench (Figure 8). The focal depths are shallow off the coast, becoming progressively deeper as events occur farther inland. The earthquake of May 22, 1960, occurred in the southern portion of this region. Based on the distribution of aftershocks, estimates are that the area of the ruptured surface may have been as large as 100,000 square kilometers.

Interest in earthquake effects in offshore areas has greatly increased in recent years. As Figure 8 shows, the shallowest depth earthquakes occur in the area toward the coast from the offshore trench. Interest in possible offshore oil in the Gulf of Alaska has led to extensive studies of earthquake motion in such areas. During the 1964 Prince William Sound earthquake, a large area of southern and offshore Alaska was uplifted several meters. This movement or displacement of several seconds' duration occurred as the upper plate, which had been dragged down by the lower plate, was released, sliding up over the lower plate. No motions have been recorded in the "near field" in great earthquakes, but this displacement pulse has been observed in several California earthquakes.

A magnitude 5.7 event on a thrust fault occurred offshore from Santa Barbara, California, on August 13, 1978. This earthquake produced peak ground acceleration of up to 0.45 gravitational acceleration on onshore instruments. Because of equipment difficulties, no records were obtained from any of the offshore oil platform instruments. As mentioned previously, strong-motion instruments are started by a trigger mechanism. Operational vibrations had triggered these instruments so frequently that they had run out of recording film. A record obtained on the Hondo platform, erected in 1976 in 260 meters of water, would have been especially interesting. The displacement pulse effect was evident to those who were on that platform during the earthquake. Supply boats frequently nudge the tall tower structure, causing a slow, gentle displacement that can be felt by those on the platform. So they first thought the platform had been nudged by a boat, but, when the deflection became larger, they realized that it was an earthquake. The single large displacement during the shaking appears to have been the result of the displacement pulse propagated into the near field from the fault rupture.

Along coasts, large earthquakes can bring on additional horror. A sudden fault displacement that produces seismic stress waves can produce long water waves, called tsunamis, on the ocean surface. Although not noticeable in the deep ocean, the height of these waves can increase greatly as they approach a coastline, often crashing with disastrous effects. Figure 9 shows the bore from a tsunami in the mouth of the Wailuku River, Hilo, Hawaii. Part

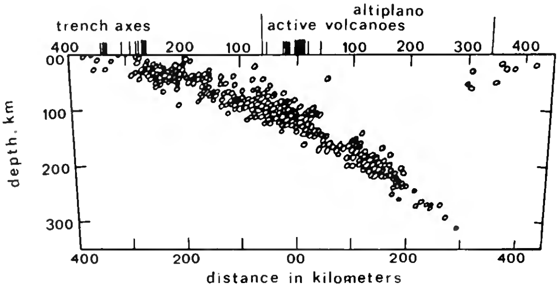


*Figure 8. Section across northern Chile, where depths of earthquakes increase as Pacific plate is subducted beneath the South American plate.*

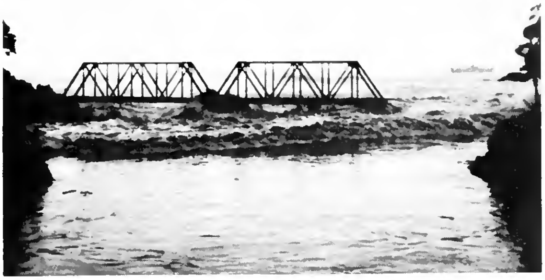


*Figure 9. Bore from a tsunami entering mouth of Wailuku River near Hilo, Hawaii. One span of the bridge was destroyed by an earlier wave. (Courtesy NOAA)*

of the bridge had already been destroyed by an earlier wave from the same tsunami. Except in the case of a very strong earthquake, where casualty losses have been very high, a large tsunami washing ashore usually is much more destructive than the direct effects from shaking. This was true during the earthquake in Alaska in 1964, where a tsunami caused severe damage in ports, such as at Kodiak and Seward. The tsunami also traveled in four and a half hours to Crescent City, California, where, despite warnings, more damage and further fatalities occurred. The total tsunami damage exceeded $100 million, with 119 fatalities.

Not all tsunamis are accompanied by crashing waves. Two large earthquakes of magnitude near 8 occurred during July of 1971 south of Rabaul, which is located on the east end of the island of New Britain in Papua New Guinea. Both of these events produced tsunamis in Rabaul Harbor. In this case, however, the water rose and fell like an exceptionally high tide for 30 minutes, with no structural damage.

Because grand-scale plate movement occurs continuously, strain accumulation is released as fault slip at nearly regular intervals. Therefore if two areas have experienced slippage by earthquakes and an area between has not, it is reasonable to conclude that an earthquake is more likely to occur in the central region. Such areas are called seismic gaps. Figure 10 shows the location of possible seismic gaps along the Pacific/Caribbean margin. The dark zones are the shallow seismic belts. Major earthquakes have not occurred for 30 years in some places within the blank areas along these belts. The Mexican earthquakes south of Oaxaca, on November 29, 1979, and Guerrero, on March 14, 1978, occurred in recognized seismic gaps.

The earthquake that occurred in Alaska on February 28, 1979, near Icy Bay, is of more interest (Figure 11). It is believed that this event extended over only a portion of the seismic gap, which raises the possibility that other large events may be imminent because this area was subjected to three

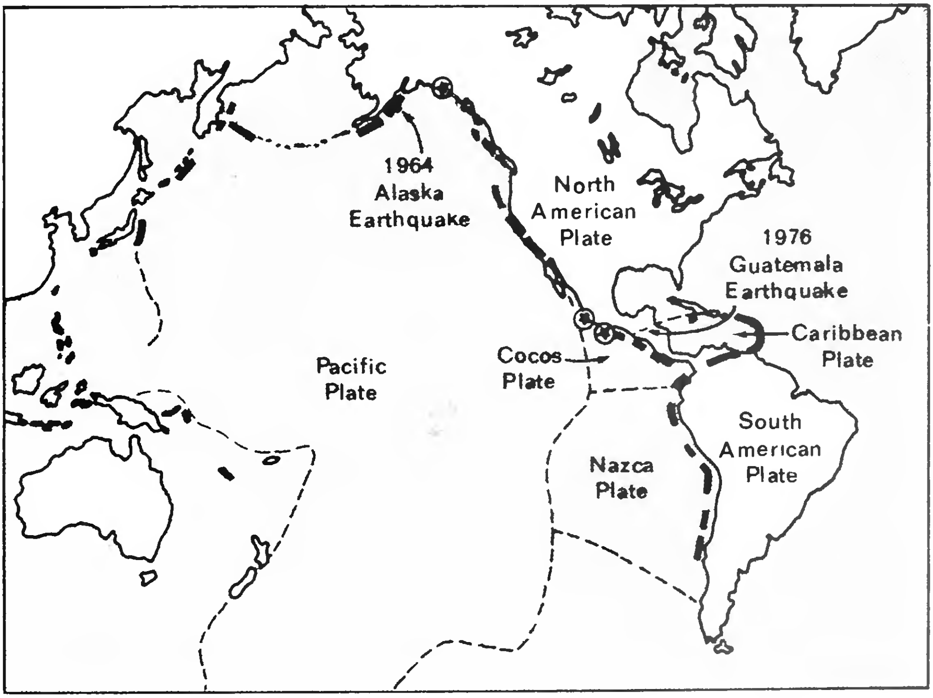


*Figure 10. Pacific Ocean margin. Dotted lines indicate the approximate plate boundaries. Possible gaps in eastern Pacific are between the heavy lines. Open circles show recent events believed to have occurred in recognized seismic gaps.*

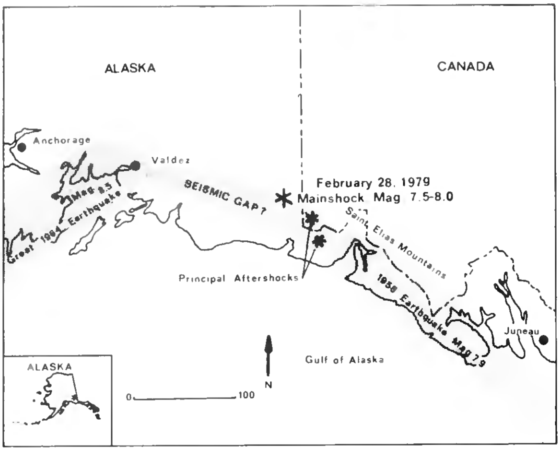


*Figure 11. Events that are believed to have occurred in a portion of a seismic gap in Alaska. (Courtesy USGS)*

closely-spaced events of magnitudes near 8 in 1899 and 1900. Observations relating to seismic premonitory phenomena, however, are not restricted to seismic gaps. Other observations include measurement of the accumulation of stress within the crust, and accurate geodetic measurements of displacements occurring across fault zones that will ultimately result in earthquakes.

The ability to predict when and where earthquakes will occur is still very imprecise. The Chinese had spectacular success in predicting an earthquake in Liaoning Province in February, 1975, which saved many thousands of lives. They also have had predictions that have not been successful. There was no forewarning of the tragic earthquake of July, 1976, which almost destroyed the city of Tangshan, resulting in an estimated 650,000 deaths.

Because earthquakes are so sudden and buildings in many areas inadequate, the number of fatalities is often very large. More than 19,000 people were killed during an earthquake on September 16, 1978, near Tabas in eastern Iran. Whole villages were destroyed. Construction in rural Iran consists primarily of single-story structures with adobe walls and earth roofs. The thickness of soil on the roof provides insulation from the heat, but is fatal to occupants during an earthquake. It would appear that if earthquake-resistant buildings were available, many future fatalities could be avoided. The solution, however, is not that simple. Following an earthquake in Iran in 1952, some villages were reconstructed using seismic-resistant designs, but, because the buildings required a change in lifestyle, the villagers refused to live in them and instead rebuilt their old-style dwellings. Social conditions also can lead to an increase in hazards. In Guatemala, many buildings are built of *bajareque* (wood and lath frames covered with a mud plaster). These withstand shaking better than adobe, which has almost no resistance to ground shaking. Adobe houses, however, are more socially desirable.

Within the seismic areas of the United States, the majority of newer construction is relatively safe. Wood frame houses and steel high-rise buildings are known to perform well during earthquakes. No structures can be built economically to resist displacement if they lie across a fault or in the path of a tsunami. While new construction is designed to resist earthquake shaking, the majority of residential areas are often older apartment buildings built of brick or masonry without reinforcement. These represent the major seismic hazard within the cities. It is a hazard that professionals recognize, but one that the public at large has not yet faced.

*Neville Donovan was educated in New Zealand and the United States in the fields of geotechnical and structural engineering. After finding difficulties in interpreting seismological data for engineering use, he entered the fields of engineering seismology and earthquake engineering, attempting to bridge the information gap between seismologists, geologists, and the practicing engineer. In so doing, he has visited earthquake sites in many countries. He is a Principal Engineer and Partner in the San Francisco, California, office of the firm of Dames and Moore.*

**Selected Readings**

Barazangi, M., and J. Dorman. 1969. World seismicity maps compiled from ESSA coast and geodetic survey epicenter data, 1961-1967. *Bull. Seismol. Soc. Amer.* 59(1): 369-80.

Bolt, B. A. 1978. *Earthquakes: a primer.* San Francisco, CA: W. H. Freeman & Co.

Donovan, N. C., B. A. Bolt, and R. V. Whitman. 1979. Development of expectancy maps and risk analysis. *Journal of Structural Division*, A.S.C.E., 104: ST8.

Hanks, T.C., and D. A. Johnson. 1976. Geophysical assessment of peak accelerations. *Bull. Seismol. Soc. Amer.* 66(3): 915-36.

Kanamori, H. 1978. Quantification of great earthquakes. *Tectonophysics* 49: 207-212.

Uyeda, S. 1978. *The new view of the earth.* San Francisco, CA: W. H. Freeman & Co.

# Sea-Level Changes During the Tertiary

*The edge of the sea is a continually changing line affected by the height of the adjacent land and the height of the sea. While the height of the land is determined by local geological conditions and varies from place to place, the height of the sea is essentially the same everywhere. Over long periods of time, the height of the sea surface, or sea level, can also change for reasons that are not entirely clear.*

*This interplay of land and sea elevations can cause a complex distribution of the land-derived sediments carried out to sea along the continental margins. By learning to decipher this complex layering of sediments, the geologist can gain information about both geological conditions along the coast and global sea-level changes. He can learn of paleoenvironmental conditions along the seashore and about conditions that may have been conducive to the formation of petroleum — **The Editors***

**by Peter R. Vail and Jan Hardenbol**

Studies of global changes in sea level throughout geological history are important to hydrocarbon exploration as an instrument of stratigraphy and geochronology, especially in areas that lack well or outcrop information. Sedimentation, responding to changes in sea level, has produced a unique stratigraphic record by shaping sedimentary sequences that can be studied by seismic reflection. Recent studies of continental margins utilizing seismic reflection, well, and shallow core data have provided a mass of new information on sea-level fluctuations. Cycles of relative rise and fall of sea level have been charted in many regions and found to be synchronous on a global basis. Depositional effects related to these global cyclic controls are overprinted on regional tectonic and sedimentary effects.

Cycles of relative changes of sea level, even when simultaneous on a global scale, do not exactly reflect true eustatic* changes. This is because thick sedimentary sections, which undergo considerable subsidence during their formation, are necessary to determine sea-level changes. Therefore, relative changes of sea level, even when they occur simultaneously on all continents, may be caused by a change in eustatic sea level, simultaneous subsidence, or, as is usually the case, a combination of both factors. Simultaneous uplift on a global scale is not indicated by our continental margin studies.

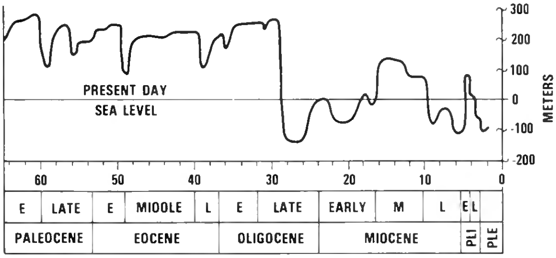


*Figure 1. Tertiary eustatic changes of sea level. Meters above or below sea level are tentative. Correlation of numerical ages with faunal zones is shown in Figure 8. (Adapted from Vail, and others, 1977)*

### Tertiary Eustatic Sea-Level Changes

Our best estimate of Tertiary eustatic sea-level changes is shown in Figure 1. The horizontal axis shows geologic age in millions of years. The vertical axis is calibrated in meters above and below present sea level. The eustatic curve shows an overall trend of falling sea level throughout the Tertiary Period (from 65 million to 2 million years ago). Our studies indicate sea level reached a maximum height of more than 300 meters greater than present-day sea level late in the Cretaceous (136 million to 65 million years ago). Our studies also show a large number of rapid falls and rises of sea level superimposed on the overall trend of falling sea level. The falls appear to be very rapid, occurring over a period of a million years or so, and many of them appear to have a magnitude of more than 100 meters. The largest fall is late in the Oligocene Epoch (approximately 29 million years ago) with a probable fall of considerably more than 200 meters in a period of

---

*Eustatic sea level is defined as worldwide changes of sea level that affect all oceans.

one to two million years. The dates of the major falls are 60, 49.5, 40, 29, 22.5, 10.8, 6.6, and 4.2. Lesser falls occurred between these times, as indicated in Figure 1.

The subject of worldwide simultaneous sea-level changes is very controversial. Most researchers agree that sea level reached a high point in the Late Cretaceous and has fallen since then. The controversy involves the magnitude of the change from Late Cretaceous to Recent, and the existence of rapid falls of sea level of more than 100 meters in a period of a million years or so. Several scientists have concluded that sea level was more than 300 meters higher in the Late Cretaceous than now. Other researchers believe that the value is significantly lower, somewhere between 100 and 150 meters. The existence of large, rapid falls of sea level is an especially controversial subject. In addition, some scientists recognize the existence of global relative changes of sea level on continental areas, but believe they are the result of simultaneous earth movements (tectonic events), and not eustatic changes of sea level.

### Procedure for Determining Sea-Level Changes

The recommended procedure for determining global changes of sea level consists of three steps:

1. *Determine relative changes of sea level by identifying regional unconformities (gaps in continuous sedimentation) and determining the age and distribution of coastal and marine onlap.**
2. *Compare regional curves of relative changes of sea level to a global curve to indicate anomalies that may be related to regional tectonic or local structural events.*
3. *Determine eustatic changes of sea level by analyzing rates of subsidence and uplift.*

Eustatic changes of sea level can be estimated directly from Step 3 without involving Steps 1 and 2. Our experience has shown, however, that Step 3 performed independently for individual wells commonly leads to significant problems in determining overall magnitudes of sea-level change and in recognizing short-term changes even of large magnitude. Significant errors in estimates of the magnitude of sea-level changes will result if regional tectonic events or local structures that cause an uplift or reduction in subsidence rates are not recognized. Such events will commonly be detected in conjunction with the regional stratigraphic analysis associated with Steps 1 and 2. Unconformities resulting from erosion or nondeposition are critical in identifying short-term sea-level changes. These are not always evident from analysis of individual wells and may be missed.

### Determination of Relative Changes of Sea Level

Figure 2 illustrates our approach for interpreting relative changes of sea level from seismic data or detailed well log* stratal correlation patterns. A relative change of sea level is an apparent rise or fall of sea level with respect to the land surface. Either eustatic sea level, the land surface, or both in combination may rise or fall during a relative change. Figure 2 shows three diagrams. The upper one represents a stratigraphic cross section. The thin black lines are chronostratigraphic horizons that represent the interpretation of seismic reflections or well log stratal correlations. The wavy lines are unconformities or their correlative equivalents. Discontinuities caused by onlap, downlap, or erosion of sediments can be recognized from changes in seismic reflection patterns. These unconformities mark the boundaries of each sedimentary sequence — A to E in Figure 2b. Thus the sedimentation events of the past are recreated and noted on what is called a chronostratigraphic chart. In Figure 2b, geological time instead of depth is plotted on the vertical axis. Ages range from 25 million years to present. The advantage of the chronostratigraphic diagram is that it shows the hiatuses from erosion and nondeposition, and separates out the individual sequences. We date the unconformities at the age when they become conformable. For example, the unconformity between A and B is 17.5 million years, B and C 13.5, and so on. In this manner we assign a quantitative age to each unconformity. These ages bound an interval of geologic time in which all the rocks of a sequence are deposited. The chronostratigraphic chart portrays the missing strata within the time intervals.

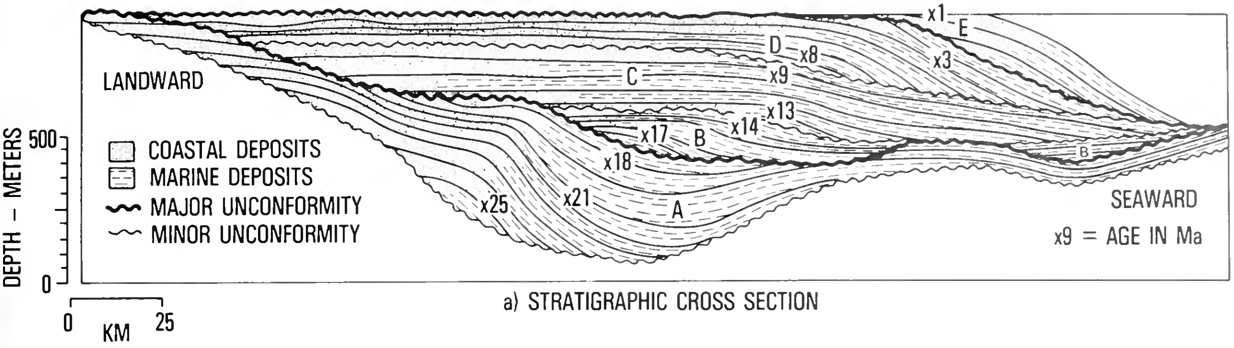
Relative changes of sea level are determined from the onlap of coastal deposits over the unconformities and the distribution of highstand and lowstand** deposits. Other methods may be

---

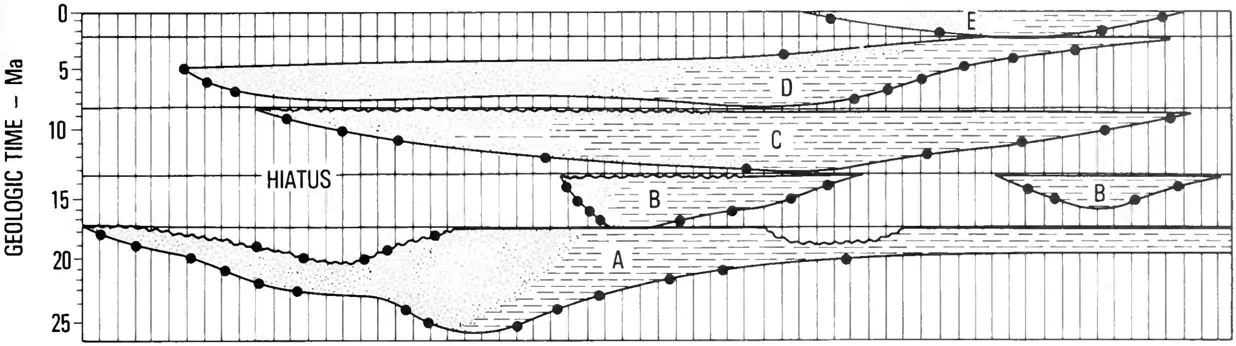
*Extension of successive stratigraphic units beyond the marginal limits of their predecessors onto older rocks as in the deposits of a transgressing sea.

*Record of a well, generally a lithologic record of the strata penetrated.

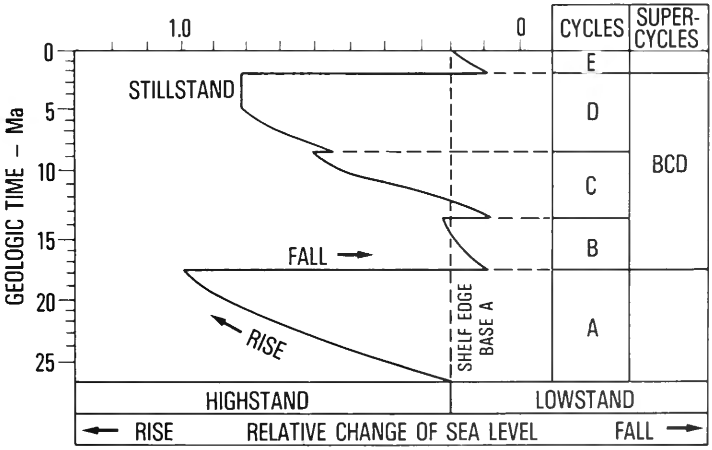
**A highstand is defined as the interval of time when sea level is above the shelf edge, and a lowstand as the interval of time when sea level is below the shelf edge. A comparative lowstand may be recognized when sea level is at its lowest position on the shelf during the deposition of a series of sequences. Both situations result from a fall in sea level. Lowstand deposits result when the rate of eustatic sea-level fall is faster than the rate of subsidence and comparative lowstands result when the rate of eustatic sea-level fall is less than the rate of subsidence.



a) STRATIGRAPHIC CROSS SECTION



b) CHRONOSTRATIGRAPHIC CHART



c) REGIONAL CHART OF CYCLES OF RELATIVE CHANGES OF SEA LEVEL

*Figure 2. Procedure for constructing chart of cycles of relative changes of sea level. (Adapted from Vail, and others, 1977)*

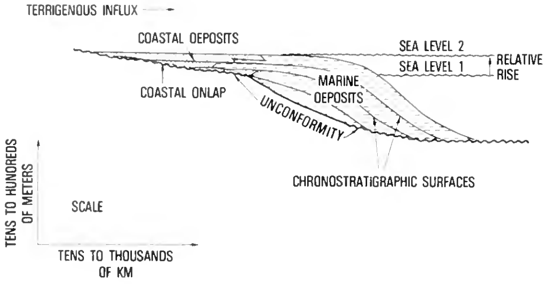


*Figure 3. Coastal onlap indicates a relative rise of sea level. Relative rise of base level allows coastal deposits of a sequence to aggrade and onlap underlying unconformity. (After Vail, and others, 1977)*

employed to help measure relative changes of sea level, but there are pitfalls in using alone such phenomena as transgression/regression of the shoreline and deepening/shallowing of the sea bottom.

A relative rise of sea level is an apparent sea-level rise with respect to the underlying unconformity (Figure 3), and is indicated by coastal onlap. It may result from (1) the sea level actually rising, while the underlying unconformity remains stationary, or rises at a slower rate; (2) sea level remaining stationary, while the underlying unconformity subsides; or (3) sea level falling, while the underlying unconformity subsides at a faster rate. Coastal onlap is the progressive landward onlap of littoral and/or nonmarine coastal deposits in a given sequence.

During a relative rise of sea level, where the sedimentary supply is sufficient, coastal deposits progressively onlap the underlying unconformity. The process is unable to build above sea level, which approximates the effective depositional base level. Without the relative rise of sea level, coastal onlap would cease.

The onlapping coastal deposits of a particular sequence may have been removed by erosion at a given locality. In some cases, the missing strata may be restored to a projection of the underlying unconformity, sometimes with the help of isolated erosional remnants.

During a relative rise of sea level, a transgression or regression of the shoreline and deepening or shallowing of the sea bottom may take place. Marine transgression and regression during a relative rise of sea level are illustrated in Figure 4. A transgression of the shoreline is indicated by landward migration of the littoral (coastal) facies in a given stratigraphic unit, and a regression is indicated by seaward migration of the littoral facies. Instead of undergoing transgression or regression, the shoreline may be stationary. Similarly, a deepening of the sea bottom (Figure 4) is normally indicated by evidence of increasing water depth,* and a shallowing of the sea bottom is indicated by evidence of decreasing water depth. Instead of deepening or shallowing, the sea bottom may remain constant. However, regression and shallowing can occur during a relative rise, stillstand, or fall of sea level, owing to variations in the rates of subsidence and sediment supply, while the reverse can be true of transgression.

On a seismic section recorded across the coastal facies of a sequence, a relative rise of sea level can be recognized by onlapping reflections. Transgressions and regressions of a shoreline are recognized with more difficulty by lateral changes in reflection characteristics, such as amplitude, frequency, wave form, and interval velocity, indicating changes from coastal to marine facies.

A relative fall of sea level is an apparent fall of sea level with respect to the underlying unconformity, indicated by a downward shift of coastal onlap. It may result: (1) if sea level actually falls, while the underlying unconformity rises, remains stationary, or subsides at a slower rate; (2) if sea level remains stationary, while the unconformity is rising; or (3) if sea level rises, while the unconformity is rising at a faster rate.

A downward shift of coastal onlap is a shift downslope and seaward from the highest position of coastal onlap in a given sequence to the lowest position of coastal onlap in the overlying sequence. In Figure 5, the downward shift occurs between the highest coastal onlap of Unit 5 in Sequence A and the lowest coastal onlap of Unit 6 in Sequence B. The patterns of onlap indicate a relative rise of sea level during deposition of Sequence A, then an

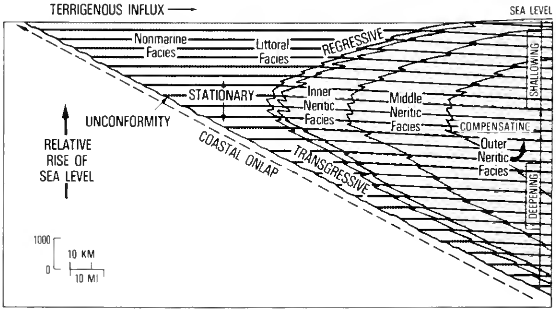


*Figure 4. During a relative rise of sea level, as evidenced by coastal onlap, littoral facies may be transgressive, stationary, or regressive, and neritic (continental shelf) facies may be deepening, compensating, or shallowing. (After Vail, and others, 1977)*

---

*Fossil organisms, such as molluscs or foraminifera, can provide indications of a preferred depth habitat, but seismic reflection patterns also permit identification of certain environments.

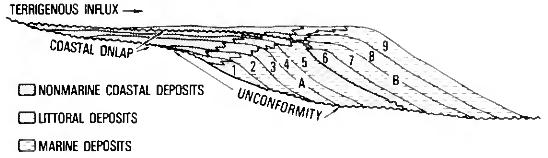


*Figure 5. Downward shift of coastal onlap indicates relative fall of sea level. With relative fall of base level, erosion is likely; deposition is resumed with coastal onlap during subsequent rise. (After Vail, and others, 1977)*

abrupt relative fall to the position of Unit 6 in Sequence B, followed by another relative rise during deposition of Sequence B.

The stratification pattern in Figure 6 shows a downward shift in coastal facies patterns. It indicates deposition during a relative fall of sea level. This pattern is uncommon. An example is the lower Gallup Formation in New Mexico, where several falls in a short period of time produced a similar pattern.

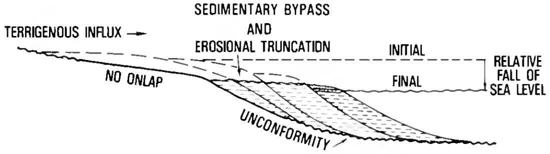


*Figure 6. Downward shift in coastal facies pattern indicates deposition during a relative fall of sea level. This is an uncommon pattern. (After Vail, and others, 1977)*

In areas where regional subsidence proceeds at a faster rate than any fall of sea level, a relative rise is produced. Therefore, an actual gradual fall in sea level might not be detected by using coastal onlap as a criterion.

Where a sea-level fall is faster than subsidence, the shelf tends to be bypassed, and the area of coastal onlap may be restricted to the apex of a fan at the basin margin. Figure 7 shows differences in stratal patterns during periods of highstand and lowstand of sea level.

A marked change in the depositional pattern of deep-marine strata commonly occurs as a result of sea level falling more rapidly than subsidence. Figure 7a illustrates an idealized pattern developed during a highstand of sea level, when shallow seas covered much of the shelf. Deposition occurs in clinoform* lobes that prograde across the shallow shelf; with sufficient sediment supply, the progradation continues into deep water as shown in this illustration. Coarse clastics** tend to be trapped on the shelf, and finer material is transported to the toes of the clinoforms. Figure 7b illustrates the depositional pattern after a rapid fall of sea level below the shelf edge. The shelf is exposed to subaerial erosion, and rivers tend to bypass the shelf and deposit directly onto the slope. During the ensuing rise of sea level, any coastal onlap occurs near the sediment source. Most of the onlap commonly occurs in marine deposits at the proximal edge of a submarine fan, as shown in Figure 7b. Marine onlap may extend into very deep water. This overall lowstand pattern is diagnostic of a major fall of sea level and is common along continental margins and in deep-marine basins.

The preceding discussion shows how to recognize cycles of relative rise and fall of sea level using coastal onlap and the distribution of highstand and lowstand deposits. These changes can be plotted as curves of relative change of sea level, as shown in Figure 2c. In this example, each cycle of relative change of sea level is asymmetrical, with a slow rise to stillstand and then a rapid fall. This asymmetry of cycles has been observed in the investigations to date. It is due to the sensitive nature of the interaction between rates of eustatic sea level falls versus rates of subsidence.

The cycles as a group also show a pattern of asymmetry. Cycle A represents a highstand, cycles B, C, and D begin with a lowstand, gradually rising to a highstand, and cycle E is a lowstand. A higher order cycle (supercycle) BCD is recognized by the progressive rise and fall within the asymmetrical pattern.

Knowledge of relative changes of sea level can be helpful in predicting sedimentary events. For example, the highstands are the most likely times for trapping terrigenous clastics in deltas on the shelf, and the lowstands are the most likely times that the clastics will be funneled through submarine canyons or other notches in the shelf edge and deposited in submarine fans in the basin.

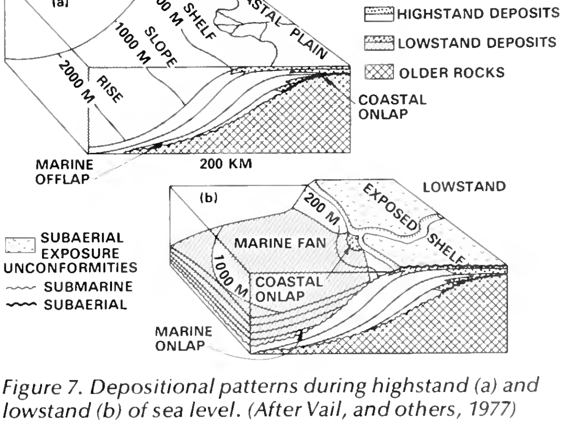


*Figure 7. Depositional patterns during highstand (a) and lowstand (b) of sea level. (After Vail, and others, 1977)*

---

*The subaqueous land form, analogous to the continental slope.

---

**Fragments of rock moved from their place of origin.

### Comparison of Regional and Global Curves

Cycles of relative change of sea level on a global scale are present throughout the Tertiary Period. The evidence is based on the fact that many regional cycles determined on different continental margins and interior basins are simultaneous and that the relative magnitudes of the changes generally are similar. Figure 8 shows the global cycles of relative changes of sea level for the Tertiary Period. The vertical axis of each chart is scaled in millions of years with standard periods and epochs plotted alongside. The horizontal axis shows relative positions of sea level and is scaled from 1.0 to 0.0, with 1.0 being the maximum relative highstand (68 million years ago) and 0.0 being the minimum relative lowstand (29 million years ago). Relative rises of sea level are plotted toward the left and relative falls toward the right. The present position of sea level is extended through Tertiary time as a vertical reference line. A global cycle of relative change of sea level is an interval of geological time during which a relative rise and fall of sea level takes place on a global scale. Intermittent stillstands (and therefore paracycles) may occur in any part of the cycle.

The ages and durations of the Tertiary cycles are determined mainly from grids of seismic data tied to wells. Age documentation is based mainly on planktonic foraminifera zones that have been tied to the geochronometric scale. Amplitudes of the relative changes are determined from seismic stratigraphic, well log, and outcrop studies. We are continuously obtaining new data, which result in small, but important revisions.

On the right side of the global cycle chart are columns containing ages and notations for identifying unconformities and stratigraphic units on seismic and stratigraphic sections. We name the unconformities after the oldest strata above the unconformity (for example, the basal middle Chattian) and designate it by age in millions of years (29 million years ago). Intervals between the unconformities are informally designated by symbols.

Regional curves, constructed as shown in Figure 2, can be compared with the global curve, Figure 8, to identify similarities and anomalies. Similarities indicate that the relative curve fits the global pattern and, we believe, results from global sea-level changes. Anomalies indicate local or regional events have occurred. These are commonly due to regional tectonics or local structuring. Identification of these structural events is essential for the determination of the magnitudes of eustatic sea-level changes.

### Determination of Eustatic Sea-Level Changes

The curve of global relative changes of sea level, Figure 8, shows the long-term trend of generally high sea level in the Early Tertiary with lower sea level in the Late Tertiary. In addition, it shows the relative magnitudes and timing of rapid falls and rises of sea level superimposed on the long-term trend. A critical question is, how can the absolute magnitudes and detailed shape of the eustatic changes be determined by separating the eustatic component from the subsidence component?

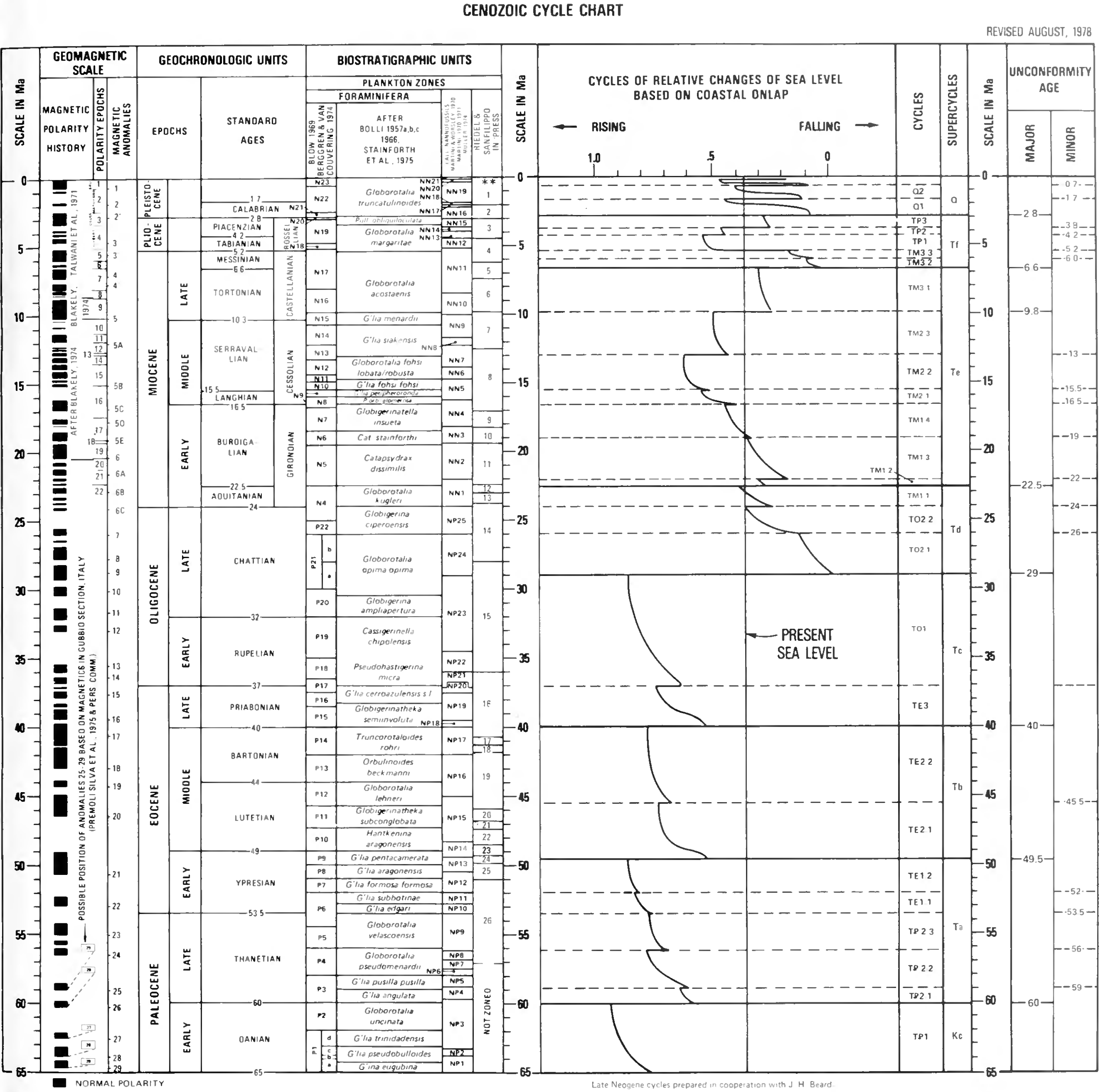
As mentioned previously, absolute magnitudes of eustatic sea-level changes are very controversial. However, many researchers in this field, including the authors, believe that the best way to determine absolute magnitude is by using subsidence or geohistory curves, described by J. E. Van Hinte, and correcting these curves for loading and compaction (loss of water) by using the techniques described by M.S. Steckler and A.B. Watts in 1978. Before applying these techniques, however, the authors believe that the times of rapid falls and rises of sea level and times of regional tectonics and local structuring must be defined by regional stratigraphic studies.

Our studies applying the three-step procedure described at the beginning of this article continue to support the overall, long-term magnitude of sea-level change of more than 300 meters above present sea level in the Cretaceous. They also support the existence of rapid sea-level falls throughout the Tertiary of at least 100 to 200 meters in a period of one million years or so. These results are summarized in Figure 1.

### Evidence for Rapid Falls in Sea Level

Figure 9 is an example of how detailed paleontological studies support the notion of rapid falls of sea level throughout the Tertiary Period. Two published studies are shown — one by F.T. Barr and W.A. Berggren and the other by Berggren and J. Aubert. Geologic time and paleontologic zonations are shown on the vertical axis and paleowater depth from neritic to middle bathyal are shown on the horizontal axis. The wide lines show the paleowater depths for three sections determined by the authors. Note the rapid shallowing of sea level of 300 to 400 meters over the one-million-year period from 50 to 49 million years. This corresponds to the major fall of relative sea level shown at 49.5 million years in Figure 8. The large number for the fall of sea level of 300 to 400 meters results from direct paleontologic observation with no corrections and thus is probably larger than the true sea-level fall. Nevertheless, the data do support a rapid fall of sea level of considerable magnitude at the time predicted by the charts of eustatic and relative change of sea level, Figures 1 and 8.

Figures 10 and 11 illustrate the expression of rapid falls of sea level on strike and dip seismic sections located near the shelf edge offshore from West Africa. Geohistory analysis indicates that the shelf virtually ceased to subside and became



Stratigraphic chart Revision J Hardenbol and F M Weaver

Late Neogene cycles prepared in cooperation with J H Beard

Paleogene and Early Neogene cycles prepared in cooperation with J Hardenbol & J Lamb

Revision cycles P R Vail and J Hardenbol

Notations (e g , $TE^{1\ 1}$) may be used to designate sequences and super sequences on seismic sections, etc

**RADIOLARIAN ZONES

1 Lamprocyrtis haysi
2 Pterocanium prismatium
3 Spongaster pentas
4 Stichocorys peregrina
5 Ommatartus penultimus
6. Ommatartus antepenultimus
7 Cannartus petterssoni
8 Dorcadospyris alata
9 Calocycletta costata
10 Stichocorys wolffii
11 Stichocorys delmontensis
12 Cyrtocapsella tetrapera
13 Lychocanoma elongata
14 Dorcadospyris ateuchus
15 Theocyrtis tuberosa
16 Thyrsocyrtis bromia
17 Podocyrtis goetheana
18 Podocyrtis chalara
19 Podocyrtis mitra
20 Podocyrtis ampla
21 Thyrsocyrtis triacantha
22 Theocampe mongolfieri
23 Theocotyle cryptocephala
24 Phormocyrtis striata striata
25 Buryella clinata
26 Bekoma bidartensis

*Figure 8. Global cycles of relative change of sea level during the Tertiary. (After Vail and Mitchum, 1979)*

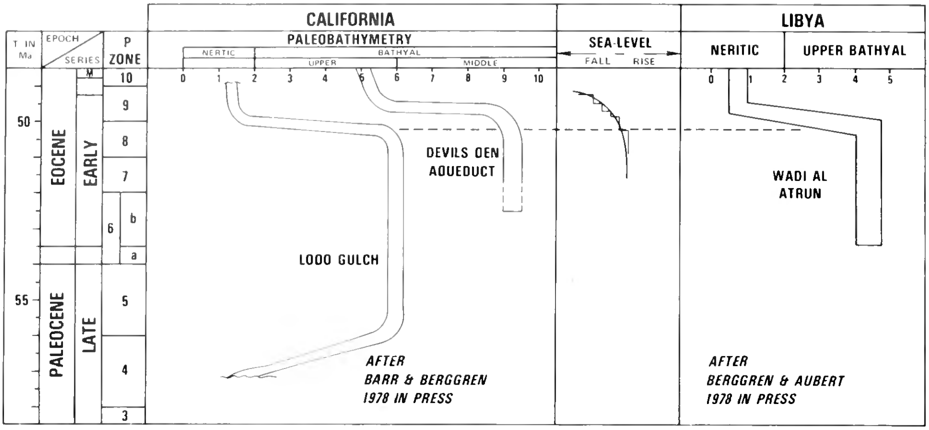


*Figure 9. Paleontologic evidence for rapid falls of sea level.*

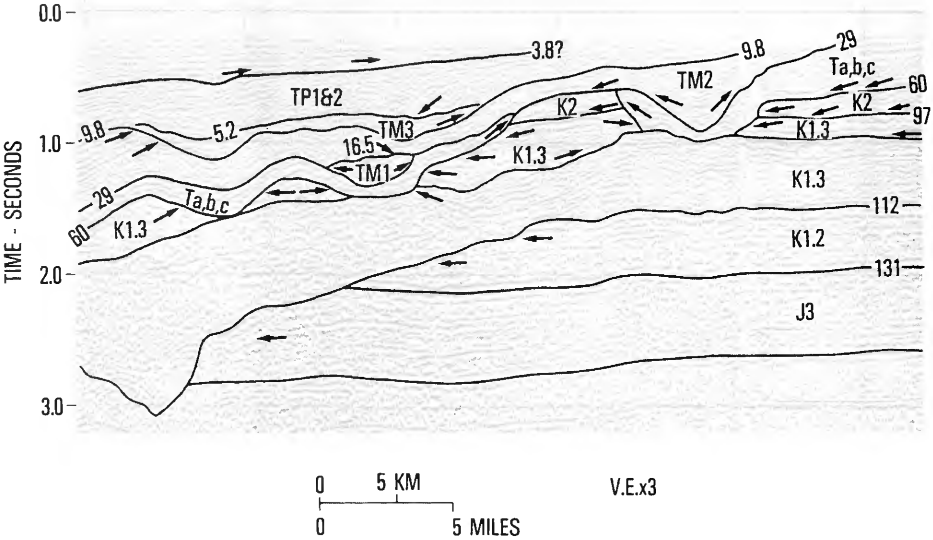


*Figure 10. Seismic line parallel to shelf edge offshore from West Africa, showing erosional and depositional patterns of Tertiary strata.*

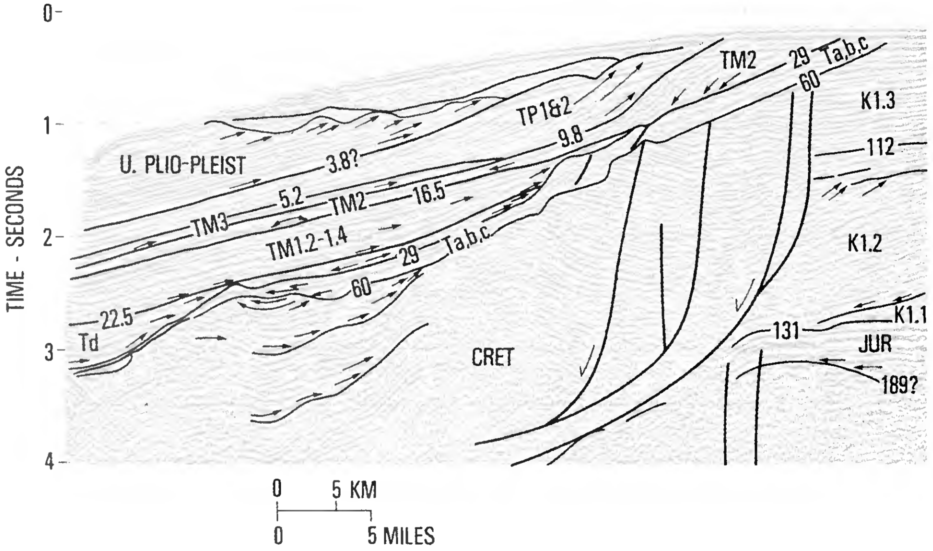


*Figure 11. Seismic line perpendicular to shelf edge offshore from West Africa, showing erosional and depositional patterns of Tertiary strata.*

stable in the mid-Cretaceous. We believe the unconformities 60, 29, 22.5, 10.8, and 6.6 were all caused by rapid falls of sea level during the Tertiary Period. During intervening times, normal deposition took place. Lowstand times Td, TM1.2-1.4, TM3, and TP3 exhibit the characteristic deep marine onlap patterns of marine fans shown in Figure 7b. Highstand times of Ta-b-c, TM2, and TP1 are characterized by prograding deltas of deep marine hemi-pelagic drape facies (Figure 7a). The landward portions of the deltas are truncated. We believe they once extended landward across the shelf, during higher stands of the sea, but have subsequently been eroded away during the intervening lowstands.

Our information indicates the unconformities correspond to rapid falls in sea level, and, we believe, are caused by these rapid falls. However, the unconformities can be traced down the slope to abyssal water depths, and must in large part be formed by submarine processes.

Several wells penetrated the Tertiary strata in this area, and were used to date the age of the section. No wells are present on the two seismic lines shown. Ages shown are based on correlating sequence boundaries on a grid of seismic data tied to the available wells.

## Looking Ahead

There is no question that considerably more research needs to be undertaken to document the magnitudes and timing of eustatic sea-level changes. The techniques and data are now becoming available to carry out this research in the manner outlined in this article. If the rapid changes of eustatic sea level discussed here are verified by further research, the causes of these changes need to be determined. Glaciation is the only known mechanism that occurs rapidly enough to cause such rapid changes in sea level. However, there is no evidence yet for glaciation during the lowstand periods of the Early Tertiary Period. The long-term fall of eustatic sea level from the Late Cretaceous to its present-day level is most likely caused by an increase in volume of the ocean basins as a result of lower rates of sea-floor spreading and continental collisions.

*Peter R. Vail is a Research Scientist at the Exxon Production Research Company, Houston, Texas. Jan Hardenbol is a Research Associate in the same company.*

## References

Barr, F. T., and W. A. Berggren. In press. Lower Tertiary biostratigraphy and tectonics of northeastern Libya. In *Second symposium on the geology of Libya*, Tripoli, September 1978. London: Academic Press.

Berggren, W.A., and J. Aubert. In press. Paleogene benthonic foraminiferal biostratigraphy and bathymetry of the central coast ranges of California. USGS Prof. Papers.

Campbell, C.V. 1979. Model for beach shoreline in Gallup sandstone (upper Cretaceous) of northwestern New Mexico. New Mexico Bureau of Mines and Mineral Resources, Circular No. 164, p. 32.

Gary, M., R. McAfee, Jr., and C.L. Wolf. 1972. *Glossary of geology*. Washington, D.C.: American Geol. Inst.

Hardenbol, J., and W.A. Berggren. 1978. A new paleogene numerical time scale. In *Contributions to the geologic time scale*. AAPG Studies in Geology 6:213-34.

Pitman, W.C. 1978. Relationship between sea-level change and stratigraphic sequences. *Geol. Soc. Am. Bull.* 89:1389-1403.

Ryan, W.F.B., M.B. Cita, M.D. Rawson, L.H. Burcicle, and T. Saito. 1974. A paleomagnetic assignment of neogene stage boundaries and the development of isochronous datum planes between the Mediterranean, the Pacific, and Indian Oceans in order to investigate the response of the world ocean to the Mediterranean salinity crisis. *Riv. Italiana Paleontologia* 80(4):631-88.

Sleep, N.H. 1976. Platform subsidence mechanisms and "eustatic" sea-level changes. *Tectonophysics* 36:45-56.

Sloss, L.L. 1976. Areas and volumes of cratonic sediments, western North America and Eastern Europe. *Geology* 4:272-76.

Steckler, M.S., and A.B. Watts. 1978. Subsidence of the Atlantic-type continental margin off New York. *Earth and Planetary Science Letters* 41:1-13.

Vail, P.R., R.M. Mitchum, Jr., R.G. Todd, J.M. Widmier, S. Thompson III, J.B. Sangree, J.N. Bubb, and W.G. Hatlelid. 1977. Seismic stratigraphy and global changes of sea level. In *Seismic stratigraphy — applications to hydrocarbon exploration*. AAPG Memoir 26:49-212.

Vail, P.R., R.M. Mitchum, Jr., T.H. Shipley, and R.T. Buffler. In press. Unconformities of the North Atlantic. *Phil. Trans. R. Soc. London*.

Vail, P.R., and J. Hardenbol. 1979. (Abstract.) Canadian Soc. Pet. Geol. and Canadian Soc. of Expl. Geop. Joint Convention, Calgary, Alberta, June 10-13, 1979.

van Hinte, J.E. 1978. Geohistory analysis — application of micropaleontology in exploration geology. *Am. Assoc. Pet. Geol. Bull.* 62(2):201-222.

Watts, A.B., and M.S. Steckler. 1979. Subsidence and eustasy at the continental margin of eastern North America. In *Deep drilling results in the Atlantic Ocean*, Ewing Series Vols. 2 and 3. Washington, D.C.: AGU.

Weller, J.M. 1960. *Stratigraphic principles and practices*. New York: Harper.

# Oceanus Back Issues

Limited quantities of back issues are available at prices indicated; a 25 percent discount is offered on orders of five or more. PLEASE select alternatives for those in *very limited supply.* We accept only prepaid orders. Checks should be made payable to Woods Hole Oceanographic Institution; checks accompanying foreign orders must be payable in U.S. currency and drawn on a U.S. bank. Address orders to: Oceanus Back Issues, 1172 Commonwealth Ave., Boston, MA 02134.

**ENERGY AND THE SEA,** Vol. 17:5, Summer 1974 — One of our most popular issues. There is extractable energy in the tides, currents, and temperature differences; in the winds that blow over them; in the very waters themselves. Eight articles discuss these topics as well as the likelihood of finding oil under the deep ocean floor and of locating nuclear plants offshore. **$4.00**

**MARINE POLLUTION,** Vol. 18:1, Fall 1974 — Popular controversies, such as the one over whether or not the seas are "dying," tend to obscure responsible scientific effort to determine what substances we flush into the ocean, in what amounts, and with what effects. Some progress is being made in the investigation of radioactive wastes, DDT and PCB, heavy metals, plastics and petroleum. Eleven authors discuss this work as well as economic and regulatory aspects of marine pollution. **$4.00**

**FOOD FROM THE SEA,** Vol. 18:2, Winter 1975 — Fisheries biologists and managers are dealing with the hard realities of dwindling stocks and increasing international competition for what is left. Seven articles deal with these problems and point to ways in which harvests can be increased through mariculture, utilization of unconventional species, and other approaches. **$4.00**

**DEEP-SEA PHOTOGRAPHY,** Vol. 18:3, Spring 1975 — A good deal has been written about the use of hand-held cameras along reefs and in shallow seas. Here eight professionals look at what the camera has done and can do in the abyssal depths. Topics include the early history of underwater photography, present equipment and techniques, biological applications, TV in deep-ocean surveys, the role of photography aboard the submersible *Alvin* along the Mid-Atlantic Ridge, and future developments in deep-sea imaging. **$4.00**

**MARINE BIOMEDICINE,** Vol. 19:2, Winter 1976 — *Very limited supply.* **$3.00**

**ESTUARIES,** Vol. 19:5, Fall 1976 — Of great societal importance, estuaries are complex environments increasingly subject to stress. The issue deals with their hydrodynamics, nutrient flows, and pollution patterns, as well as plant and animal life — and the constitutional issues posed by estuarine management. **$4.00**

**SOUND IN THE SEA,** Vol. 20:2, Spring 1977 — Beginning with a chronicle of man's use of ocean acoustics, this issue covers the use of acoustics in navigation, probing the ocean, penetrating the bottom, studying the behavior of whales, and in marine fisheries. In addition, there is an article on the military uses of acoustics in the era of nuclear submarines. **$3.00**

**GENERAL ISSUE,** Vol. 20:3, Summer 1977 — The controversial 200-mile limit constitutes a mini-theme in this issue, including its effect on U.S. fisheries, management plans within regional councils, and the complex boundary disputes between the U.S. and Canada. Other articles deal with the electric and magnetic sense of

Oceanus
The Illustrated Magazine
of Marine Science
Published by Woods Hole
Oceanographic Institution

SUBSCRIPTION ORDER FORM

Please make checks payable to Woods Hole Oceanographic Institution.
Checks accompanying foreign orders must be payable in U.S. currency and drawn on a U.S. bank.
(Outside U.S., Possessions, and Canada add $2 per year to domestic rates.)

Please enter my subscription to OCEANUS for

☐ one year at $10.00
☐ two years at $18.00

☐ payment enclosed.
(we request prepayment)
☐ bill me

Please send MY Subscription to:

Name (please print) ______
Street address ______
City ______ State ______ Zip ______

Please send a GIFT Subscription to:

Name (please print) ______
Street address ______
City ______ State ______ Zip ______
Donor's Name ______
Address ______

Oceanus
The Illustrated Magazine
of Marine Science
Published by Woods Hole
Oceanographic Institution

SUBSCRIPTION ORDER FORM

Please make checks payable to Woods Hole Oceanographic Institution.
Checks accompanying foreign orders must be payable in U.S. currency and drawn on a U.S. bank.
(Outside U.S., Possessions, and Canada add $2 per year to domestic rates.)

Please enter my subscription to OCEANUS for

☐ one year at $10.00
☐ two years at $18.00

☐ payment enclosed.
(we request prepayment)
☐ bill me

Please send MY Subscription to:

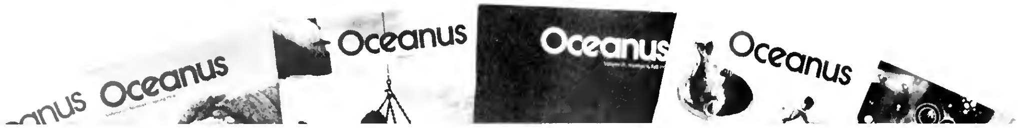
Name (please print) ______
Street address ______
City ______ State ______ Zip ______

Please send a GIFT Subscription to:

Name (please print) ______
Street address ______
City ______ State ______ Zip ______
Donor's Name ______
Address ______

GENERAL ISSUE, Vol. 19:4, Summer 1976

*HIGH-LEVEL NUCLEAR WASTES IN THE SEABED?* Vol. 20:1, Winter 1977



PLACE
STAMP
HERE

Oceanus
Woods Hole Oceanographic Institution
Woods Hole, Mass. 02543

PLACE
STAMP
HERE

Oceanus
Woods Hole Oceanographic Institution
Woods Hole, Mass. 02543

issue covers the use of acoustics in navigation, probing the ocean, penetrating the bottom, studying the behavior of whales, and in marine fisheries. In addition, there is an article on the military uses of acoustics in the era of nuclear submarines. **$3.00**

**GENERAL ISSUE,** Vol. 20:3, Summer 1977 — The controversial 200-mile limit constitutes a mini-theme in this issue, including its effect on U.S. fisheries, management plans within regional councils, and the complex boundary disputes between the U.S. and Canada. Other articles deal with the electric and magnetic sense of sharks, the effects of tritium on ocean dynamics, nitrogen fixation in salt marshes, and the discovery during a recent Galápagos Rift expedition of marine animal colonies existing on what was thought to be a barren ocean floor. **$3.00**

**OIL IN COASTAL WATERS,** Vol. 20:4, Fall 1977 — *Very limited supply.* **$3.00**

**THE DEEP SEA,** Vol. 21:1, Winter 1978 — Over the last decade, scientists have become increasingly interested in the deep waters and sediments of the abyss. Articles in this issue discuss manganese nodules, the rain of particles from surface waters, sediment transport, population dynamics, mixing of sediments by organisms, deep-sea microbiology — and the possible threat to freedom of this kind of research posed by international negotiations. **$3.00**

**MARINE MAMMALS,** Vol 21:2, Spring 1978 — Attitudes toward marine mammals are changing worldwide. This phenomenon is appraised in the issue along with articles on the bowhead whale, the sea otter's interaction with man, behavioral aspects of the tuna/porpoise problem, strandings, a radio tag for big whales, and strategies for protecting habitats. **$3.00**

**GENERAL ISSUE,** Vol. 21:3, Summer 1978 — The lead article looks at the future of deep-ocean drilling, which is at a critical juncture in its development. Anther piece — heavily illustrated with sharp, clear micrographs — describes the role of the scanning electron microscope in marine science. Rounding out the issue are articles on helium isotopes, seagrasses, red tide and paralytic shellfish poisoning, and the green sea turtle of the Cayman Islands. **$3.00**

**OCEANS AND CLIMATE,** Vol. 21:4, Fall 1978 — This issue examines how the oceans interact with the atmosphere to affect our climate. Articles deal with the numerous problems involved in climate research, the El Niño phenomenon, past ice ages, how the ocean heat balance is determined, and the roles of carbon dioxide, ocean temperatures, and sea ice. **$4.00**

**HARVESTING THE SEA,** Vol. 22:1, Spring 1979 — Although there will be two billion more mouths to feed in the year 2000, it is doubtful that the global fish harvest will increase much beyond present yields. Nevertheless, third world countries are looking to more accessible vessel and fishery technology to meet their protein needs. These topics and others — the effects of the new law of the sea regime, postharvest fish losses, long-range fisheries, and krill harvesting — are discussed in this issue. Also included are articles on aquaculture in China, the dangers of introducing exotic species into aquatic ecosystems, and cultural deterrents to eating fish. **$3.00**

**GENERAL ISSUE,** Vol. 22:2, Summer 1979 — This issue features a report by a group of eminent marine biologists on their recent deep-sea discoveries of hitherto unknown forms of life in the Galápagos Rift area. Another article discusses how scuba diving is revolutionizing the world of plankton biology. Also included are pieces on fish schooling, coastal mixing processes, chlorine in the marine environment, drugs from the sea, and Mexico's shrimp industry. **$3.00**

**OUT OF PRINT**

***SEA-FLOOR SPREADING,*** Vol. 17:3, Winter 1974
***AIR-SEA INTERACTION,*** Vol. 17:4, Spring 1974
***THE SOUTHERN OCEAN,*** Vol. 18:4, Summer 1975
***SEAWARD EXPANSION,*** Vol. 19:1, Fall 1975
***OCEAN EDDIES,*** Vol. 19:3, Spring 1976
***GENERAL ISSUE,*** Vol. 19:4, Summer 1976
***HIGH-LEVEL NUCLEAR WASTES IN THE SEABED?*** Vol. 20:1, Winter 1977

(ISSN 0029-8182)
WOODS HOLE
OCEANOGRAPHIC
INSTITUTION
Woods Hole, MA 02543
Postmaster: Please Send
Form 3579 to Above Address

SECOND-CLASS
POSTAGE PAID
AT FALMOUTH, MASS.,
AND ADDITIONAL
MAILING POINTS