the Theory of Seismology (Cambridge Univ. Press, Cambridge, ed. 3, 1963).
8. E. Wiechert, *Nachr. Ges. Wiss. Gottingen Math.-Phys. Kl.* (1897), p. 221.
9. R. D. Oldham, *J. Geol. Soc. (London)* **62**, 456 (1906).
10. B. Gutenberg, *Nachr. Ges. Wiss. Gottingen Math.-Phys. Kl.* (1914), p. 1; *ibid.*, p. 125.
11. I. Lehmann, *Bur. Centre Seismol. Int. A* **14**, 3 (1936).
12. H. H. Turner, *Mon. Not. R. Astron. Soc. (Geophys. Suppl.)* **1**, 1 (1922).
13. K. Wadati, *Geophys. Mag. Tokyo* **8**, 305 (1935).
14. J. Barrell, *J. Geol.* **22**, 655 (1914).
15. B. Gutenberg, *Geol. Soc. Am. Bull.* **65**, 337 (1954).
16. F. A. Cook, L. D. Brown, J. E. Oliver, *Sci. Am.* **243** (No. 4), 156 (1980).
17. S. B. Smithson, J. A. Brewer, S. Kaufman, J. E. Oliver, C. Hurick, *J. Geophys. Res.* **84** (B11), 5955 (1979).
18. L. D. Brown, C. E. Chapin, A. R. Sanford, S. Kaufman, J. E. Oliver, *ibid.* **85** (B9), 4773 (1980).
19. Continental Scientific Drilling Program (Geophysics Research Board, National Academy of Sciences, Washington, D.C., 1979).
20. D. J. De Paolo, *Eos* **62** (No. 14), 138 (1981).
21. W. M. Elsasser *et al.*, *J. Geophys. Res.* **84** (B1), 147 (1979).
22. R. B. Smith and R. L. Christiansen, *Sci. Am.* **242** (No. 2), 104 (1980).
23. *Dynamics of the Lithosphere: the Framework for Earth Resources and Reduction of Hazards* (Interunion Commission on the Lithosphere Report 1, International Lithosphere Program, c/o Geodynamics Program Office, Mail Code ERG-2, National Aeronautics and Space Administration, Washington, D.C. 1981).
24. U.S. Geodynamics Committee, "Geodynamics in the 1980's" (National Academy of Sciences, Washington, D.C., 1980).

Ocean Crustal Dynamics

Manik Talwani and Marcus Langseth

Summary. The study of oceanic crust continues to be important because of the presence of economic resources in oceanic areas and because many fundamental problems of geologic evolution are best solved from studies of the ocean. Although modeling and syntheses of existing data remain important, key breakthroughs in the future will come from the application of new technology such as multichannel towed seismic arrays, deep-towed side scan sonars, improved thermal probes, deep drilling, and satellite altimeters.

Much current research in earth science is based on applying the plate tectonic model to problems as diverse as continental orogeny, paleoceanography, and metallogeny. Plate tectonics, developed in large part from geophysical and geological information gathered from the world's oceans, is now playing a key role in explaining the geological events and processes that shaped the continents.

The growth in interest in continental geology has led some in the earth science community to consider geophysical and geological research in the oceans to be less important now than research on land. Among the reasons given are that the first-order problems of the geological development of the oceanic basins are solved, whereas those of the continents are not, and that continental geologic research will better serve society and its need for natural resources.

We suggest, however, that marine geological research continues to be important, for the following reasons.

1) Important economic resources reside in the deep-sea and submerged margins.

2) Subduction of the oceanic lithosphere plays an important role in shaping the continents, and the major zones of active underthrusting occur mostly beneath the sea. The processes that occur in subduction zones are poorly understood, and the relative ease and smaller expense of using geophysical techniques at sea offers the best hope of unraveling these processes.

3) There remain many important problems in the evolution of the oceans, such as the role of hydrothermal circulation in the chemistry of seawater and the alteration of the crust, the origin and deep structure of backarc basins, and their relation to subduction.

4) The fundamental problem of what drives plate tectonics is best investigated over the oceanic plates.

The directions that research in marine geology and geophysics will take was the subject of a series of workshops sponsored by Joint Oceanographic Institutions. In summary of the report of this group's Ocean Crustal Dynamics Planning Committee, Hussong (*1*) states that new technology will be extremely important for research in earth sciences at sea. During the past decade new tools, such as the deep-sea drilling ship *Glomar Challenger*, multichannel seismic profiling, deep submersibles, and satellite altimeters, have allowed scientists to sample and sound deeper and with greater resolution and discrimination than the standard tools of marine geology and geophysics that opened the door to modern research in the oceans. These standard tools, largely developed in the 1950's, still have a role to play in rapid surveys and reconnaissance work; but to attack current problems, more powerful and incisive techniques are needed.

At the same time that new techniques were being developed, a change in philosophy has occurred in the research community. This change results in part from the success of plate tectonics and its simple kinematic models for testing observations, which altered the thrust of earth science research, turning it away from exploration and fieldwork toward review and synthesis of existing data and the formulation of successful earth models. One effect of this change is that today relatively few students in geoscience have an interest in the exploratory phase of research.

The emphasis on synthesis and modeling has helped us understand processes that shape and change the face of the earth. But progress may be slow in the 1980's if new data and techniques that would allow a more profound look into the earth go undeveloped.

To illustrate the importance of the role of new technologies, we discuss some outstanding geological problems in areas familiar to all geologists—passive margins, convergent margins, and the oceanic crust—and show how new techniques might help solve these problems.

M. Talwani is professor of geological sciences and M. Langseth is senior research associate and adjunct professor, Lamont-Doherty Geological Observatory, Palisades, New York 10964, and Department of Geological Sciences, Columbia University, New York 10027.

0036-8075/81/0703-0022$02.00/0

Passive Margins

Our understanding of the structure and genesis of passive continental margins (Fig. 1) is limited. The structures and rocks formed or altered at the time of the splitting apart of a continent are buried below a thick prism of sediments; existing geophysical techniques are either unable to probe beneath this thick cover or yield results that cannot be unambiguously interpreted. Although the sediments under the continental shelf are relatively well explored and sampled, those under the continental slope are poorly sampled. As the search for hydrocarbons moves into areas of greater water depth, it becomes increasingly important both to establish the geological and tectonic framework of the margins and to sample sediments buried under the continental slope. Thus, we need to understand the geophysical and tectonic events that take place before, during, and after the breakup of the continents, the ages of these events, and how they are connected to each other.

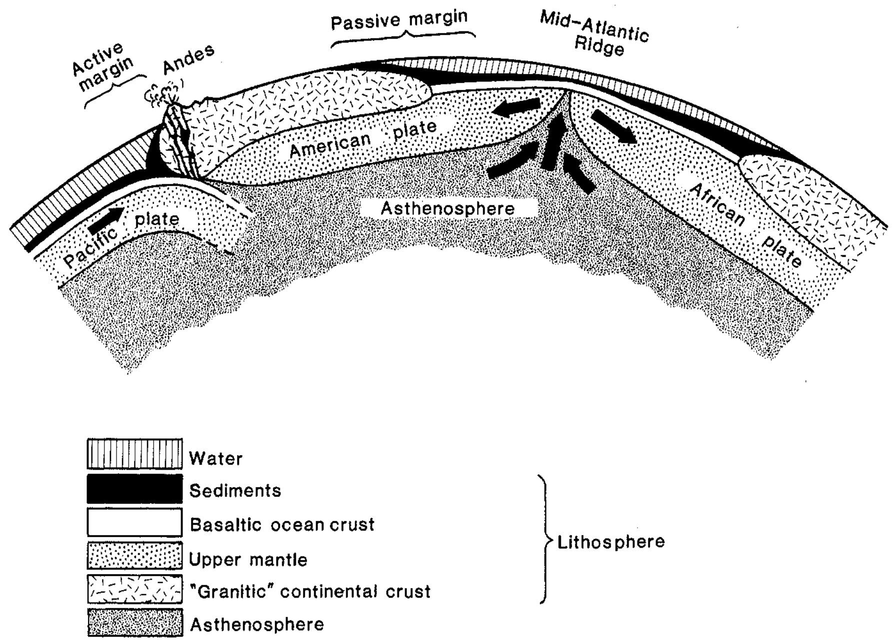


Fig. 1. Passive margins, active margins, and the Mid-Atlantic Ridge are depicted in the framework of plate tectonics.

Among the major questions that we need to answer are the following. Was there heating of the mantle and doming of the crust prior to rifting? Are continental separation and drift always preceded by an episode of extensive normal faulting or rifting? How long is the episode of rifting? Are there many small rifts or is there one principal rift? How much crustal thinning takes place and is it caused mainly by rifting due to crustal extension or are there other causes? What are the reasons for the subsidence of the continental margins and at what rates does it proceed? What is the nature of the sediments that are deposited on the subsiding continental crust and what is their thermal history? What is the nature of the newly formed oceanic crust? What sediments are deposited in the newly formed ocean and what is their organic content and thermal history?

The extent and limits of our knowledge about passive margins can be illustrated from studies of the margin of the East Coast of the United States, which has been studied intensively. (We recognize that there are large differences in tectonic style and age between the many passive margins on the earth.) Geophysical data on this margin include total intensity magnetic measurements made from ships and airplanes, gravity measurements, and seismic reflection and refraction measurements. Seismic refraction measurements are based on work with explosives carried out by the two-ship method largely in the 1950's and 1960's as well as some measurements from sonobuoys.

Multichannel seismic reflection data along a number of lines on the East Coast margin of the United States have been obtained by the U.S. Geological Survey (USGS). Line 25 (Fig. 2), which extends from the shelf across the Baltimore Canyon sediment basin to the continental slope, is one of the best examples. Figure 3 shows a structural section obtained from this multichannel seismic line together with the total intensity magnetic profile. The same seismic reflection data were used by Grow (*2*) to make the geological cross section shown in Fig. 4. (Grow used a slightly different magnetic profile from a nearby location which features a prominent magnetic spike.)

For reasons that are not clear, it has been difficult to obtain good seismic refraction data along continental margins. Grow used available data on the depth of a layer with seismic wave velocity of 7.2 kilometers per second, and one value of the depth to the mantle (defined by a velocity of 8.3 km/sec) to set the depth of these layers in Fig. 4. The location of the crust-mantle interface is derived from gravity information and some simplified assumptions about densities. Finally, the COST (Continental Offshore Stratigraphic Testing) B-3 well drilled on the upper slope calibrates the top seismic layers (Figs. 3 and 4).

Important questions in the study of passive margins concern how far areas of continental and oceanic crust extend and where the boundary between the two areas is located. Seismic reflection surfaces that are rough produce a rather typical reflection record. Sharp corners in the reflecting surface produce diffraction hyperbolas. Oceanic basement, which has a typically rough surface, has a characteristic reflection record. The identification of the reflecting horizon in Figs. 3 and 4 as oceanic basement and of the underlying area as oceanic crust is based largely on the appearance of this horizon in the reflection records. Since this horizon appears to continue landward to the East Coast magnetic anomaly, this anomaly has been adjudged the boundary between oceanic and continental crust. However, the delineation of the ocean-continent boundary in this area, a delineation that has been generally accepted, leads to some problems and raises a number of questions. First, the oceanic crust depicted here is unlike that anywhere else. The top of oceanic basement obtained by reflection studies (Figs. 3 and 4) is so close to the top of oceanic-crustal layer 3 obtained by seismic refraction studies that, because of the range of error of the seismic refraction method (*3*), the two surfaces could be the same. In that case, sediments would directly overlie material with a seismic velocity of 7.2 km/sec, a most unusual structure for the oceanic crust.

The East Coast magnetic anomaly has been associated with the landward edge of the oceanic crust. However, edge-effect calculations (*4, 5*) require that material on the landward side of the boundary be more magnetic than that on the seaward side, either by having a thicker magnetic layer or a higher intensity of magnetization. Since oceanic crust is typically more magnetic than continental crust, the juxtaposition of typical continental and oceanic crusts as shown in Fig. 4 will not produce the East Coast magnetic anomaly.

Another problem related to the passive margins is that of subsidence. From an examination of drill cores from the shelf and the deeper part of the margin, it is evident that sediments originally deposited at very shallow depths often now lie at much greater depths. For example, cores from the bottom of the COST B-3 well (Figs. 3 and 4), about 5 km down, contain Late Jurassic sediments originally deposited in a "marine-shelf to nonmarine environment" (*6*).

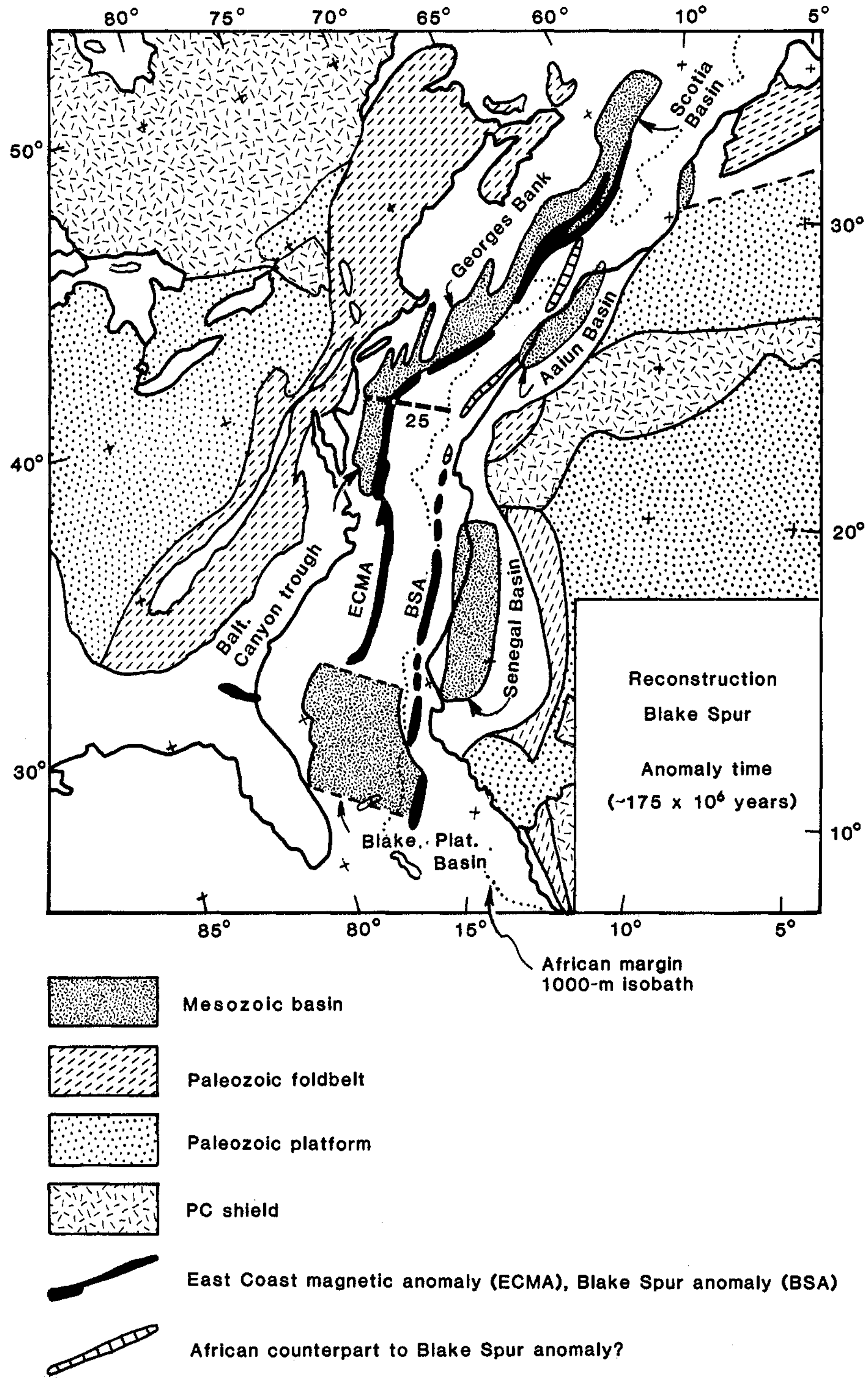


Fig. 2. Reconstruction of the North Atlantic (175 million years ago) by a westward rotation of Africa [after Klitgord and Behrendt (*54*)]. The Blake Spur magnetic anomaly, which is associated with sea-floor spreading, represents the axis of the mid-ocean ridge at this time. It is not known whether the Blake Spur anomaly represents the time of the initial opening of the North Atlantic by sea-floor spreading or whether the Atlantic Ocean had already opened, and the area between the East Coast magnetic anomaly and the Blake Spur anomaly contained oceanic crust. Although the latter is the predominant opinion, it implies that the crust underlying the Blake Plateau immediately to the south is oceanic, and many investigators doubt that.

The load of the sediments causes the crust to subside. Simple isostatic considerations, however, suggest that the amount of subsidence from this cause would be less than the thickness of the sediments that have been deposited; therefore, even a deep basin would eventually fill up with sediments. Since a major part of the shelf sediments appears to have been deposited in shallow water, sediment loading cannot be the sole cause of subsidence. A number of investigators, among them Sleep (*7*), Watts and Steckler (*8*), and Keen (*9*), have studied the North American East Coast margin to separate subsidence due to sediment loading from that due to other causes. The amount and timing of tectonic subsidence thus derived puts constraints on the models of evolution of the margin. Most models use conductive cooling and thermal contraction following crustal thinning to explain the subsidence. Different reasons have been given for the thinning. Sleep (*7*) favors crustal uplift and subsequent erosion. Artemjev and Artyushkov (*10*) and McKenzie (*11*) favor extension and necking of the continental crust. More precise knowledge about the nature and depth of deposition of sediments down to basement would allow more precise estimates of tectonic subsidence, and more precise information about the distribution and structure of sediments overlying the basement would provide clues about the timing and mechanism of crustal thinning. At present neither the nature of the crust in the critical areas of the margin nor the depth at which sediments, now deeply buried, were deposited is well known. To estimate the nature, causes, or timing of any crustal thinning is extremely difficult from existing data.

Not only is our knowledge about the deep crust scant, but knowledge about the sedimentary layers is also limited. The question marks on layer boundaries in Fig. 3 indicate the uncertainty about identification of the various seismically determined horizons. On the continental side, the deepest calibration is obtained from samples from the COST B-3 well dated at Late Jurassic in age. The identification of deeper layers is based on interpretation of seismic records and comparison with drilling results off the Canadian margin. On the oceanic side, identification of layers below J_1 (Cretaceous-Jurassic boundary) is uncertain. Furthermore, the identification of the prograding bank or reef has also not been confirmed by drill hole data.

We have emphasized the uncertainties and inadequacies of existing data in order to try to point the way toward what is needed. Drilling down to continental basement on the landward side of the East Coast magnetic anomaly to obtain samples of Jurassic and Triassic rocks and basement would be useful for many studies including subsidence studies and would calibrate the seismic stratigraphy. Drilling to positively identify the carbonate reef would also be useful as would drilling on the seaward side to calibrate seismic horizons J_2 and J_3 and to penetrate the layer identified as oceanic basement.

Obtaining deeper samples in deeper water areas is the basis for the proposed Ocean Margin Drilling Program that will use the *Glomar Explorer* as a drilling platform. This program will sponsor development of very deep penetration capability (total depth, 11 km) and a riser system to completely control circulation for use in water up to 4 km deep.

Improved seismic reflection methods have added considerably to our knowledge of the margin. For example, USGS line 25 (Fig. 3) indicates that a buried basement ridge at the edge of the continental shelf, as proposed originally by Drake *et al.* (*12*), is absent. Many more deep-penetrating seismic lines are needed to completely resolve the question of this ridge.

In areas where it has been difficult to obtain reflections by arrays of conventional length (2 to 3 km), the use of very long arrays could improve depth penetration and velocity determination. It is already possible to construct a 10-km array, with sensors 50 meters apart, for example. In the future, arrays that are 15 or 20 km in length may be possible. Alternatively, three ships in tandem, each deploying arrays 3 km long, can achieve a synthetic array 9 km in length. Such an experiment, a large aperture seismic experiment (LASE), with three ships in tandem, is scheduled for the margin off the East Coast of the United States. In the LASE experiment, the lead ship will provide the sound source with air guns, and all three ships will receive the sound signals with their arrays. A modification, in which all three ships have equivalent sound sources and receiving arrays, would allow the spacing between the ships to be increased. Even with physical gaps between the three arrays of perhaps 3 km, the system can be made to behave like a single array 21 km long with 210 channels if the shooting schedules of the three ships are synchronized properly.

Multichannel arrays on two or more ships have been used at several locations in the western Pacific and the Caribbean and Norwegian seas (*13*). The ships move away from a common point to distances of 100 or more kilometers apart. These expanded spread profile experiments yield extremely detailed wide-angle reflection and refraction information that can be used to obtain highly accurate velocity profiles in the crust and below.

If these techniques were applied to problems of the passive margin of eastern North America, it would be possible to map in detail the velocity structures from the area where it is definitely continental to the area, seaward of the Blake Spur anomaly, where it is definitely oceanic. Questions about the continent-ocean crustal boundary and the deforma-

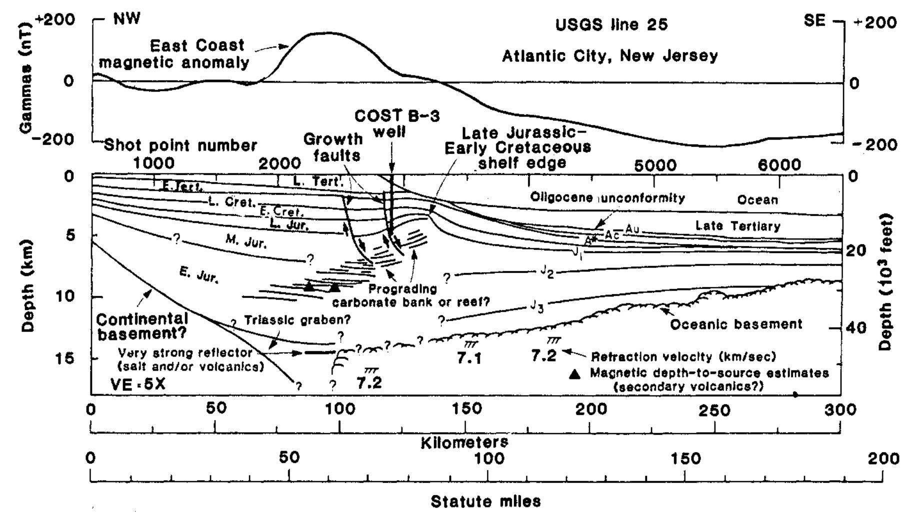


Fig. 3. Structural cross section along U.S. Geological Survey multichannel seismic line 25 (*2*); *VE*, vertical exaggeration. See Fig. 2 for location.

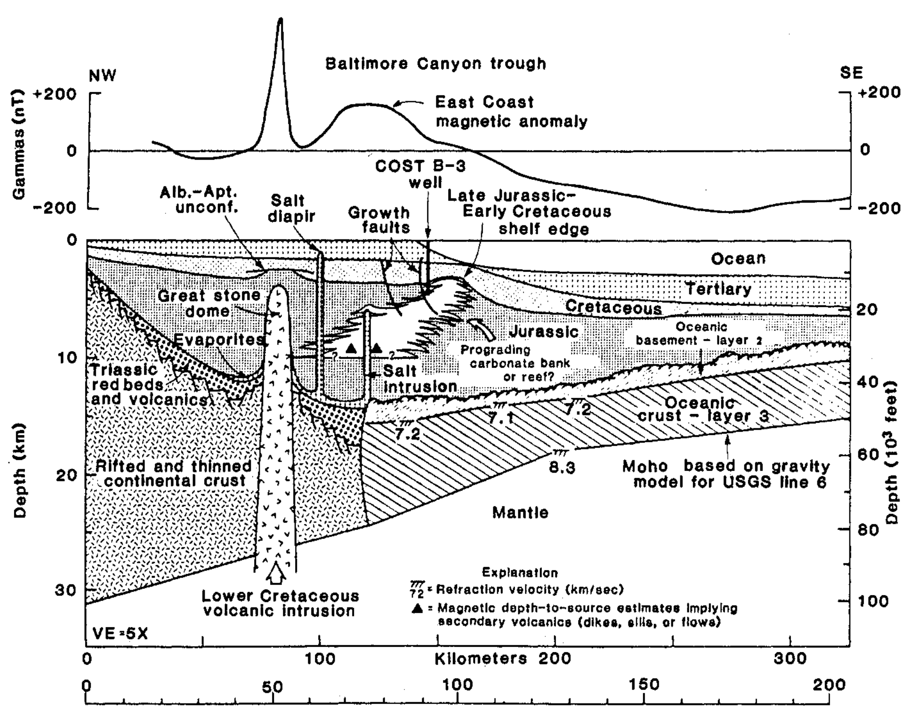


Fig. 4. Schematic crustal cross section through Baltimore Canyon trough approximately along seismic line 25; the COST B-3 well, geologic features, and geophysical parameters have been projected into the profile. Refraction data are from (*55, 56*). The crust-mantle interface is derived from gravity considerations (*2*).

tion of the crust at and after the start of continental drift might be answered. In addition, the sedimentary layers from ocean to continent could be precisely mapped.

Convergent Margins

The discoveries that resulted from drilling on the convergent margins and the problems that remain unanswered have been summarized by Hussong (*1, 14*). Among the outstanding problems of convergent margins are the following: (i) the tectonics and evolution of the forearc areas, in particular, that region of the forearc that forms the leading edge of the overthrust block; (ii) the spatial and temporal framework of subduction complexes in the Pacific during the Cenozoic; (iii) how and when deep-sea trenches are initiated; (iv) how backarc basins are formed and how they are reassimilated in the main continental blocks; and (v) how plutonism, volcanism, and metallogeny are linked to the subduction processes.

During the past 4 years, deep-sea drilling, combined with multichannel seismic profiling, has increased our understanding of the tectonics of forearc regions. During the early 1970's, kinematic models of subduction and early multichannel seismic profiles led to sedimentary accretion models (*15–17*). In brief, these models suggest that the leading edge of the forearc crust acts like a giant snowplow, scraping unconsolidated sediments off the oceanic crust as it underthrusts the margin. Continued subduction produces large prisms of sediments that accumulate on the overthrust side of trenches.

The organization of acoustic reflectors in the sediment prisms and examples exposed on land suggests that the form of deformation is imbricate overthrusting and tight folding of the sediments. Indeed, on some convergent margins such large sedimentary prisms, with imbricate style tectonics, have been illustrated. However, as the deep-sea drilling program on the active margins proceeded, it became increasingly clear that large accretion-built sedimentary prisms might be more an exception than the rule.

At the Japan Trench, evidence was found indicating that sediments brought into the trench by convergence were mostly being subducted below the forearc crust (*18, 19*). At the Japan, Mariana, and Middle America trenches, drilling results indicate that not only are sediments being subducted, but that the underside of the forearc crust is being stoped away and subducted as well. At some trenches there is virtually no accumulation of sediments on the landward wall. This erosion of the continental crust, "subduction erosion," was proposed by Rutland (*20*) and Murauchi (*21*), among others.

The consequences of subduction erosion are profound. Subduction processes not only can add to the area of continental platforms by sedimentary accretion and the incorporation of continental fragments rafted on the oceanic lithosphere, but subduction can also subtract from the total area of the continents and change the outlines of continents in a way that cannot be reconstructed. Furthermore, subduction erosion carries light, differentiated materials of the forearc crust down into the mantle, where high pressures and temperatures differentiate them again. Thus, the erosion of the forearc provides a mechanism for repeatedly refining continental materials. Another consequence of economic importance is that, in view of subduction erosion, the forearc region need not be composed of materials recently accreted that have experienced only low temperatures. Instead, a forearc region may have experienced a sedimentary, thermal, and tectonic history unrelated to the present episode of subduction, and therefore its resource potential must be assessed accordingly.

Drilling and multichannel seismic profiling have also shown that large vertical movements have occurred in forearc areas. For example, the deep shelf off of the east coast of northeastern Honshu, Japan, was shown by drilling and seismic data to have subsided nearly 3 km during the Neogene (*19*). Such rapid subsidence may record the start of subduction along this segment of the Japan Trench (*22*). Vertical movements of the overthrust block provide the main evidence about the plate tectonic history of a convergent margin (*23*). Major events, such as the initiation of subduction, consumption of an active mid-oceanic ridge, or collision between continental fragments are recorded in emergence and submergence of the forearc terrains.

Among the observations and experiments that should provide the most incisive evidence for the tectonics and history of forearc regions are drilling and detailed seismic profiling. Seismic techniques that allow high spatial resolution of acoustic stratigraphy in the rugged morphology of the trench slope are needed. A deep-towed seismic array and sound source may be one way of obtaining the required definition. Deep-sounding seismic techniques that use large aperture arrays for wide-angle and refraction experiments, similar to those proposed for passive margins, will provide definition of the deep structure of forearc platforms. Such deep sounding may be the only means to find out more about the subduction erosional process.

Detailed seismicity studies will play an important role in understanding the tectonics of subduction. Seismological observatories on the sea floor, which can be placed both landward and seaward of trenches and have recording lives of several years, would usher in a new era of precision in the location of hypocenters in these areas. The data from these observatories would provide greater definition of the deep velocity structure, more reliable determination of first motions of moderately sized events, and better data on amplitude and frequency (*24*).

Another measurement of great interest is that of stress in the vicinity of a major deep-sea trench. Such measurements may be feasible in a deeply drilled hole in the oceanic crust seaward of trenches and in the forearc. If the rocks drilled are competent enough, hydrofracture techniques can be used to determine the direction and value of maximum horizontal stress.

The role of pore waters in subduction processes. Another aspect of the subduction process only beginning to be studied is the role of pore water in the tectonics of the overthrust block. Large amounts of water contained in trench sediments (50 to 70 percent by weight) are subducted beneath the landward wall of the trench. As the sediments are compressed by the increasing lithostatic load, pore pressure rises. The increased pore pressure limits the shear strength of materials in the accretionary prism, and it also leads to upward migration of pore water.

This upward migration of pore waters may play a role in the massive slumping of sediments on the trench slope. At some level below the sea floor, the upward migration of pore waters will increase pore pressure so that it equals the lithostatic compressive load. This produces a zone of extremely low shear strength, a zone along which slumping can be easily induced by seismicity or tectonic oversteepening.

Some percentage of pore waters in subducted sediments and in oceanic crustal rocks are carried beneath the forearc crust. Murauchi and Ludwig (*25*) suggest that these waters play a role in subduction erosion. The increasing pore pressure of water in the subducted oceanic crust will force water to move up into the rocks of the overthrust block, thus decreasing the shear strength in the zone above the main plane of shearing. The shear plane then might move upward abruptly and incorporate a sliver of the forearc crust into the subducting lithosphere.

Measurements of the flow and pressures of pore waters in materials beneath the sea floor can best be made in drill holes. Measurement techniques available include standard density, sonic velocity, and temperature logs; for example, anomalously low densities in sediments might indicate high pore-water pressures, and significant departures of the thermal gradient in the hole from the geothermal gradient might indicate a vertical flow of water.

If a section of the hole can be sealed off, in situ pore pressure measurements in the rocks and flow tests to determine the hydraulic properties of the formations below the sea floor can be made. In situ determinations of porosity and permeability, as well as crack dimensions and orientations, would also contribute to our understanding of the time scale of deformation and flow in sedimentary prisms. Devices such as borehole televiewers, ultrasonic scanners that map reflectivity and hole topography, allow such determinations (*26*).

Yet another technique that will add to understanding the tectonics and mass wasting of the landward wall of trenches is the swath-mapping echo sounder that provides a three-dimensional definition of the morphology of the sedimentary wedge.

Backarc basins. Subduction complexes are not stationary features; they appear to migrate relative to the accreting boundary of the subducting plate and adjacent continents. Evidence indicates that the migration of trenches is episodic and is linked to the origin of backarc basins. The oceanic lithospheres that are the floors of backarc basins form in relatively brief periods of extensional spreading behind a migrating trench–island arc system. Usually the spreading continues only for 10 to 30 million years. Many backarc basins have been dated by magnetic lineations (*27*) and the age of others has been estimated by the mean heat-flow value (*28*). Most have ages of 40 million years or less, indicating that, on the average, backarc basins of the Pacific have relatively short lifetimes. The basins and their bounding arcs are eventually reassimilated at active margins by the long-term convergence of major plates.

Although we know very little about why or how backarc basins are formed, many have a high potential for supplying petroleum resources. Backarc basins adjacent to continental margins are often covered by 2 to 4 km of Tertiary sediments. Because of the high heat flow from the oceanic floor, much of this sedimentary layer is heated to temperatures high enough to promote maturation of organic matter in the sediments.

The majority of targets of the proposed Ocean Margin Drilling Program are in passive margins; however, the *Glomar Explorer* facility holds great promise for penetrating into the tectonized inner walls of deep-sea trenches to examine the deformation, tectonics, and metamorphism in active margins. The use of a riser with the drill string makes sediment-filled backarc basins and backarc margins potential drilling objectives.

The capability of the *Glomar Challenger* has been extended through recent innovations. One of these, the hydraulic piston corer, has opened the way for obtaining complete and nearly undisturbed stratigraphies to depths of 200 to 300 m below the sea floor. In the accretionary wedges on the landward walls of trenches, the hydraulic piston corer may be able to sample depths greater than 300 m. This would provide long intact sections of tectonized sediments and an opportunity to study the style of deformation, results of compaction, and pore-water movements.

The deep structure of island-arc and backarc basin complexes. The deep structures below subduction zones are poorly known. Studies of the gravity

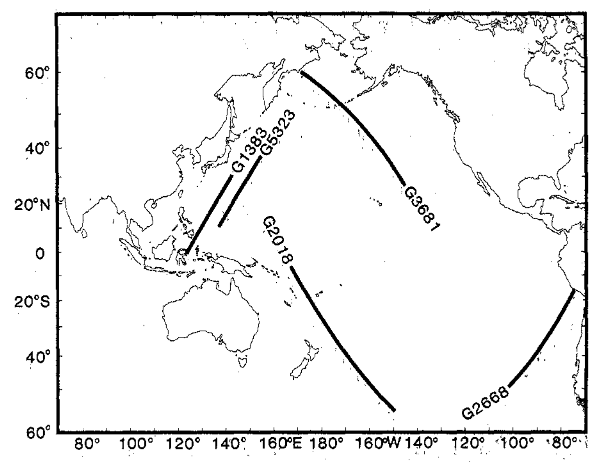


Fig. 5. Map locating GEOS-3 satellite altimeter profiles.

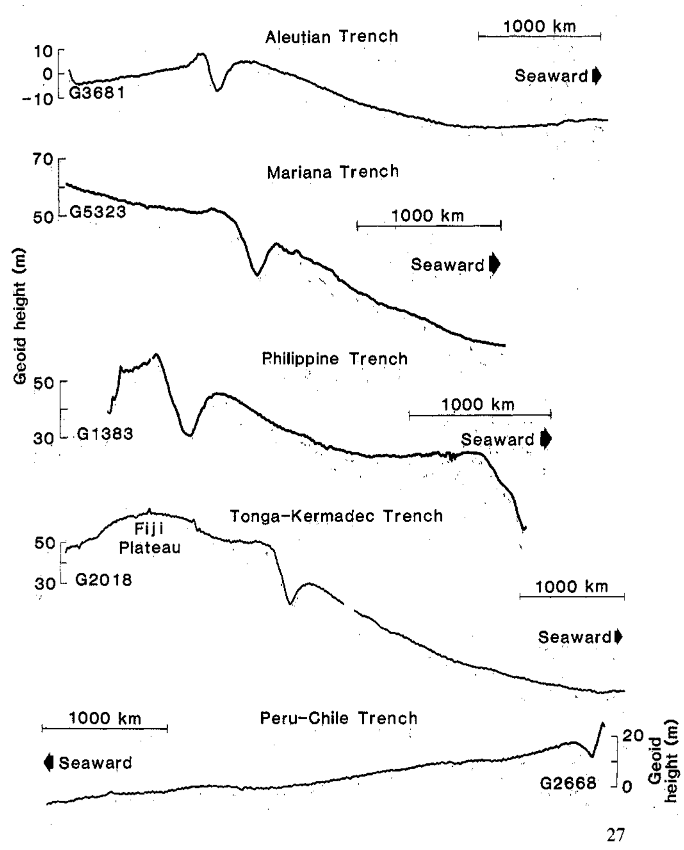
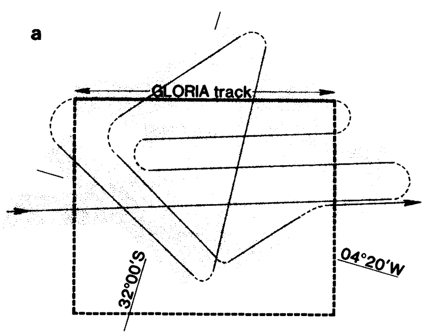


Fig. 6. GEOS-3 satellite altimeter geoid profiles across the margins of the Pacific.

field, geoidal heights, and sea-floor depths reveal some anomalies with sources deep in the mantle. Chapman and Talwani (*29*), for example, have demonstrated an increase in geoidal heights from the Pacific basin toward the island arcs and trenches (Figs. 5 and 6). They ascribe this trenchward geoidal slope to differences in mantle density beneath the convergent margins of the Pacific. Chase (*30*) and others have shown that the geoid and gravity anomalies are much smaller than expected over subducted lithospheric slabs. These data require that the excess mass of the cold downgoing slab is somehow compensated either by down bowing of the forearc area or deep-seated density differences. Studies of basement depth in North Pacific marginal basins indicate that, in comparison with the normal Pacific ocean basins, they are anomalously deeper by about 1 km (*28*), again suggesting that the density contrasts between the mantle below backarc basins and normal oceanic basins are deep seated.

A new instrument, the satellite altimeter, which can map the oceanic geoid directly, gives precise information about the gravitational field of the earth, especially in the wavelength range of about 100 to 2000 km. This instrument, first used on Skylab and then on the Geodynamics Experimental Ocean Satellite 3 (GEOS-3), was most recently employed on the Seasat satellite. The altimeter's line of signal is always oriented toward the center of mass of the earth. Radar pulses are emitted 100 times per second, and timing the reflected pulses from the sea surface gives the height of the altimeter above the sea level surface. From an accurate track of the orbit of the satellite, the height of the sea level surface with respect to a reference ellipsoid can be determined. For the GEOS-3 satellite, the sea level height determinations were averaged over a distance of about 20 km and determined to an accuracy of better than 1 m; this accuracy has been improved to a few tens of centimeters for the Seasat altimeter. Since the sea level surface is distorted, not only by the density inhomogeneities in the solid earth, but also by winds, currents, and tides, these oceanographic phenomena constitute noise that has to be allowed for in the analysis of the data.

The outstanding feature of the satellite altimeter is its ability to provide rapid and closely spaced measurements over the world's oceans; it can supply information in a range of wavelengths between those observed by surface ship gravimeters and those derived from studies of the perturbations of satellite orbits. The intermediate wavelength range information provided by satellite altimeters is most useful in examining density inhomogeneities in the upper mantle that are at depths of a few kilometers to a few hundred kilometers. Such studies will contribute to an understanding of convection in the mantle and the driving force of plate tectonics.



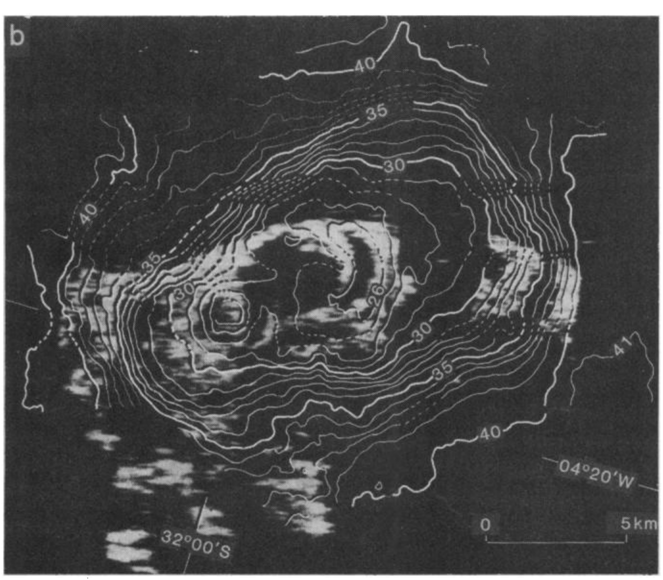


Fig. 7. (a) The track of the *Jean Charcot* for a survey over a caldera structure on the Walvis Ridge. Stippling marks the area mapped by SEABEAM. The GLORIA system was used on the single GLORIA track insonifying the area enclosed within the rectangle. (b) The results of the survey in (a). The contours are based on the SEABEAM bathymetry (much greater resolution was obtained than is indicated in the figure), and the echogram from GLORIA is superimposed. Contours are in hundreds of meters.

Oceanic Crust and Accreting Margins

The global significance of mid-oceanic ridges was recognized more than 30 years ago (*31*), and an understanding of what was happening at mid-oceanic ridge axes (*32–34*) was a key element in the formulation of global tectonic models of terrestrial evolution—that is, that ridge axes represent accreting margins of major plates. During the early 1970's, models of the petrological development and thermal evolution of the oceanic crust and the lithosphere were developed (*35, 36*), and these models successfully explained many of the first-order observations on mid-oceanic ridges.

Until about 1975, our knowledge of the mechanisms operating at mid-oceanic ridges remained rather vague, shaped by simplified models and low-resolution geophysical sounding techniques. Our understanding of the mid-oceanic ridges began to change radically when submersible and deep-towed instruments provided a closer look at the submerged portions of the ridges. The axes of the East Pacific Rise and Galápagos spreading center were found to be the sites of extraordinary hydrothermal manifestations with exotic biological communities (*37*).

Accreting plate boundaries in plan view. Once the kinematics of transform faults were understood (*38*), the general configuration of ridge axes and fracture zones were mapped by bathymetric profiles along tracks (*39*) with the aid of seismicity. During the 1970's, two new bathymetric tools came into use: the side-looking sonar system (GLORIA), developed by the Institute of Oceanographic Sciences in the United Kingdom, and the multibeam swath-mapping system (SEABEAM), developed by the U.S. Navy. Both systems provide a complete map of the sea-floor morphology but have limitations in resolution. The GLORIA system, which depends on acoustic returns from sloping surfaces on the sea floor, provides an image of reflecting surfaces for distances up to 30 km on either side of the ship (*40*). The true depth of the reflectors is not determined by the system. Figure 7 compares a GLORIA sonic "snapshot" of a caldera crater on the Walvis Ridge with bathymetry determined from the SEABEAM system on the French research ship *Jean Charcot*. The SEABEAM system, which maps the sea-floor depth within a swath on either side of the ship, uses an array of transducers and synthetic aperture techniques to analyze beams returned from the bottom. Over ridges where the sedimentation rate is low and the basement is exposed, these systems show the design and texture of the igneous oceanic crust with great clarity.

Triple junctions are particularly interesting targets for swath-mapping. Junctions where three ridges meet or two ridges and a fracture zone converge, appear to be unstable, leading to propagating rift segments (*41*) or abandoned fracture zones. These changes of configuration are frozen into the fabric of the surrounding sea floor, and swath-mapping provides a powerful technique for reconstructing the kinematics of triple junctions in recent geologic time.

The depth dimension. Although the horizontal motions of the oceanic crust, which amount to thousands of kilometers, have been studied with precision, knowledge of the properties of the oceanic crust and mantle and how they change vertically has improved relatively slowly. Two-ship seismic refraction studies have been supplemented by experiments with ocean bottom seismometers (*42, 43*) and radio sonobuoys (*44*). However, many important questions remain about the presence or absence of magma chambers under the mid-ocean ridge axes, the properties of the upper mantle under the ridge crest and how they contrast with the upper mantle under the ocean basins, and the variation in the thickness of the lithosphere from the ridge crest to the ocean basins.

The multichannel seismic towed array appears to be as promising a tool in this area as it does in the study of passive and active margins. Figure 8 from Herron *et al.* (*45*) shows a series of shallow crustal reflections obtained in a multichannel seismic reflection profile series on the East Pacific Rise at 8°N. The most prominent reflection (R4 in Fig. 8) appears to mark the top of what Orcutt *et al.* (*42*) believe is a magma chamber in the East Pacific Rise; they used ocean bottom seismometers with synthetic seismograms to model travel times and amplitudes. Herron *et al.* (*46*) have mapped the same reflections in nearby areas of the crest of the East Pacific Rise.

To map the seismic layering of the basement by the multichannel seismic reflection method often requires extensive processing of the raw data. It is generally much easier to map the boundaries between the sediment and the basement and the crust and the mantle. Figure 9 shows reflection records from the western Pacific near the Japan Trench close to the subducting edge of the Pacific plate and at the crest of the East Pacific Rise (at the accreting edge of the Pacific plate). Two features are immediately apparent. The reflection time of

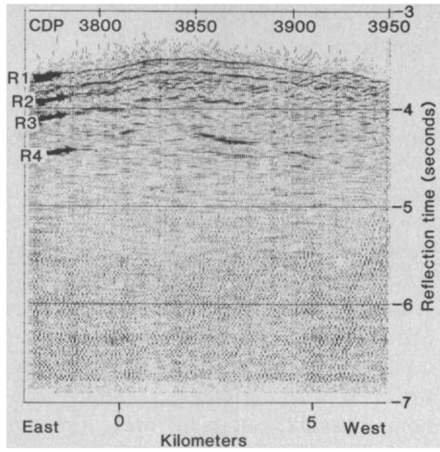


Fig. 8. The reflector R4 on the crest of the East Pacific Rise is identified as the top of a magma chamber (*42*). The reflectors were obtained by multichannel seismic reflection profiling (*46*); *CDP*, common depth point.

sound as it traverses the crust, and therefore presumably the crustal thickness, appears to be very nearly the same for the new crust as for crust which is more than 100 million years old. Second, the crust-mantle discontinuity appears as a very prominent reflector at wavelengths of about 1 km.

With longer arrays and more powerful sound sources the seismic reflection method can be extended deeper into the earth and perhaps can even be used to map the lithosphere-asthenosphere boundary. But to obtain velocities of the layers within the crust and mantle, wide-angle reflection and refraction methods must be used.

The temperature structure of the oceanic lithosphere as a function of age is a subject of great interest, particularly for ages greater than 80 million years, when significant cooling begins to reach depths of 100 km or more. Whether the lithosphere continues to cool as a half space or whether the cooling is arrested by heat brought up by convection (*47*) is not known. Studies of heat-flow measurements from the sea floor, basement elevation, and seismic surface waves have been applied to this problem without a conclusive result. Heat-flow measurements do not have the requisite accuracy, basement elevation measurements in the Mesozoic oceans are contaminated by other effects, and surface-wave paths are limited. Recently, new constraints on the deepening of isotherms with age have been deduced from studies of flexural strength of the lithosphere as a function of age (*48*). Electromagnetic recordings with instruments in the sea floor and seismic sounding with ocean bottom seismometers, long refraction profiles, and very long array seismic reflection profiles may allow investigators to sound the top of the asthenosphere. Some electromagnetic experiments have been made, but the data are sparse and difficulties with instruments still present a major obstacle.

Hydrothermal circulation and alteration of the oceanic crust. Several lines of evidence show that the igneous oceanic crust is extremely porous and permeable; this is due in part to the intense thermal fracturing that results from cold seawater penetrating the newly formed crust (*49*), in part to the voids left in the volcanic extrusive carapace, and in part to an overlay of off-axis crustal faulting that may penetrate to the base of the crust. Near the axis, seawater is involved in vigorous high-temperature hydrothermal systems (*37*); and on the ridge flanks a slower, lower temperature thermal convection prevails (*50*). The total area of sea floor affected by hydrothermal circulation is about 60 million km^2, which is roughly equal to half the land area on the earth.

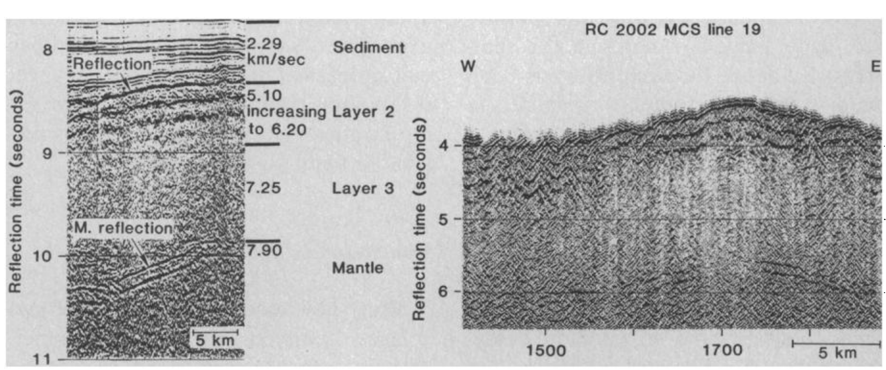


Fig. 9. Multichannel seismic reflection section on the East Pacific Rise (right) reveals a deep reflector at a reflection time of about 6 seconds (*57*). This is identified as the Moho. The double reflection time in the crust is nearly 2 seconds. The thickness of the crust is very nearly the same several thousand kilometers away at the other end of the Pacific plate near the Japan Trench (left). The top reflector at about 8.4 seconds is the top of basement and the bottom reflector, greater than 10 seconds, is Moho (*M*).

The major significance of hydrothermal circulation within the oceanic crust is its role in determining the chemistry of seawater and the alteration of basaltic oceanic crust. The circulating pore waters are an effective vehicle for chemical exchange between the basaltic oceanic crust, oceanic bottom water, and seafloor sediments. Edmonds (*51*) has estimated that within the geologically short period of 8 million years, a volume of water equal to that contained in the world ocean filters through the oceanic crust.

The 350°C water jetting from the black smokers on the East Pacific Rise at 21°N is charged with base metals leached from the crust. Precipitates of zinc, copper, and iron form the chimney-like structures from which the water pours. Under the right conditions, namely, a reducing sea-floor environment, these metal-charged waters could build massive sulfide ore bodies similar to those found in the ophiolite sequences on Cyprus and Newfoundland.

Exploration in the Mid-Atlantic Ridge axial valley has not located any perceptible emanations of warm waters; however, submersibles have explored only short segments of that ridge. Perhaps the hot rock is too deeply buried below the Mid-Atlantic Ridge to be detected by submersibles, or the crustal rocks are so fractured that cooling of the upwelling limb of the hydrothermal plume is highly effective. In the fast-spreading center, the zone of high-temperature hydrothermal activity is only a few kilometers wide. At greater distances from the axis, temperatures of circulating waters are lower because of lower rock temperatures. In addition, the sediments deposited on the flank present obstacles to free exchange between bottom water and the crust and make new chemical components available to circulating waters. Where sediments are thin and permeable, water may flow through the sediments. Evidence for such flow has been found in thermal gradients measured in all three oceans (*52*).

Measurements from recent drilling show anomalously low pore-water pressures in oceanic crust below a 270-m layer of sediments (*53*). In a hole drilled on the southern flank of the Galápagos spreading center, measurements showed pore pressures of 6 to 12 bars below hydrostatic. Similar anomalously low pressures have been observed at four other sites where drilling has penetrated basement beneath a blanket of sediment. The pressure drop between basement and ocean bottom water results in a significant drawing down of water through the hole into the basement.

These discoveries point to new areas for research in a field that might be called submarine hydrology. Most of our knowledge about the hydrology of the sea floor comes from heat-flow measurements and chemical analyses of waters emanating near the ridge axes. These are relatively blunt tools. To learn more about the pattern of circulation will require the penetration of sediments and the crust with *Glomar Challenger* technology to carry out in situ measurements of hydraulic properties, pressure, temperature, and the geochemical staining associated with circulation beneath the sea floor.

The instruments that can perform these measurements and take samples have by and large been developed by the drilling industry. Particularly important are the so-called packer techniques that allow a section of the borehole to be isolated with respect to pressure. Once the section of hole wall is isolated, representative samples of formation water can be drawn and pressure and flow rate tests carried out. From such experiments thermal, chemical, and hydrological processes in the crust can be studied. The capability of the *Glomar Challenger* is adequate for studies in layer 2 of the oceanic crust, on the flanks of ridges where low temperatures prevail.

Other new measurement techniques that can be applied to submarine hydrology problems include long vertical baseline measurements of seismic velocities and electrical resistivities. Only recently has full advantage been taken of standard logging measurements in deep-sea boreholes. For example, temperature logs provide the most sensitive data for detecting water flow and the thermal regime of oceanic basement. Eventually these studies will extend deeper into the crust, to layer 3, and closer to spreading axes where high-temperature hydrothermal processes dominate. The advanced technology planned for the *Glomar Explorer* may make such observations possible in the next decade or two.

Conclusion

Many new discoveries in marine geoscience stemmed from the development of new technological tools. In our discussion of outstanding problems in the oceans, we have attempted to show that new or improved capabilities are required if the essential data to solve these problems is to be available in the 1980's and 1990's. Three kinds of improved technologies deserve special mention. To drill in deep water with controlled circulation will require the use of the *Glomar Explorer* as proposed for the Ocean Margin Drilling Program. This is an expensive project, but the samples of rock that are crucial to the understanding of continental margins cannot be recovered by any other means. Also important are novel experiments designed around instrumentation placed in the deep holes. Second, new and improved seismic experiments with long-towed arrays and sometimes involving two and more ships are indispensable in the exploration of the oceanic crust and the thick sedimentary basins in the continental margins. Such seismic experiments are also expensive, but they are, perhaps, 30 to 50 times cheaper than comparable seismic experiments on land. Third, geological and geophysical observations made by devices close to the sea floor—and these may range from submersibles to deep-towed sonar systems—will add greatly to our knowledge of oceanic geology.

Since cost is an important factor in the application of these new technologies, imaginative ways of managing the projects that use these new technologies will have to be found in order to achieve maximum efficiency. We make this rather obvious remark because we believe it has serious implications. Marine geologists and geophysicists as well as oceanographic institutions may have to significantly alter their patterns of planning and execution of large projects and convince others that the large sums of money required for new technologies are justified and can sensibly be expected to yield important new discoveries.

References and Notes

1. D. M. Hussong, *Eos* **61**, 486 (1980).
2. J. A. Grow, *U.S. Geol. Surv. Circ. 833* (1980), pp. 117–132.
3. R. Sheridan, personal communication.
4. M. J. Keen, *Nature (London)* **22**, 72 (1969).
5. C. E. Keen and M. J. Keen, in *Geology of Continental Margins*, C. A. Burk and C. L. Drake, Eds. (Springer-Verlag, New York, 1974), pp. 381–389.
6. P. A. Scholle, in *Geology of Continental Margins*, C. A. Burk and C. L. Drake, Eds. (Springer-Verlag, New York, 1974), pp. 13–19.
7. N. H. Sleep, *Geophys. J. R. Astron. Soc.* **24**, 325 (1971).
8. A. B. Watts and M. S. Steckler, *Am. Geophys. Union Monogr.*, in press.
9. C. E. Keen, *Can. J. Earth Sci.* **16**, 502 (1979).
10. M. E. Artemjev and E. V. Artyushkov, *J. Geophys. Res.* **76**, 1197 (1971).
11. D. P. McKenzie, *Earth Planet. Sci. Lett.* **40**, 25 (1978).
12. C. L. Drake, M. Ewing, G. H. Sutton, in *Physics and Chemistry of the Earth*, L. H. A. Ahrens, F. Press, K. Rankama, S. K. Runcorn, Eds. (Pergamon, New York, 1959), vol. 3, pp. 110–198.
13. P. L. Stoffa and P. Buhl, *J. Geophys. Res.* **84**, 7645 (1979).
14. D. M. Hussong, *Episodes* **2**, 14 (1980).
15. D. R. Seely, P. R. Vail, G. G. Walton, in *Geology of Continental Margins*, C. A. Burk

and C. L. Drake, Eds. (Springer-Verlag, New York, 1974), pp. 249–260.
16. J. C. Moore and D. E. Karig, *Geol. Soc. Am. Bull.* **87**, 1259 (1976).
17. L. D. Kulm and G. A. Fowler, in *Geology of Continental Margins*, C. A. Burk and C. L. Drake, Eds. (Springer-Verlag, New York 1974), pp. 261–283.
18. M. Langseth *et al.*, *Geotimes* **23**, 22 (1978).
19. R. von Huene *et al.*, *ibid.*, p. 16.
20. R. W. R. Rutland, *Nature (London)* **233**, 252 (1971).
21. S. Murauchi, *Kaiyo-Kagaku* **7**, 537 (1975).
22. M. G. Langseth, R. von Huene, N. Nasu, H. Okada, *Oceanologica*, in press.
23. S. E. Delong and P. J. Fox, in *Island Arcs, Deep Sea Trenches, and Back Arc Basins*, M. Talwani and W. Pitman, Eds. (American Geophysical Union, Washington, D.C., 1977), pp. 221–228.
24. T. Utsu, *J. Fac. Sci. Hokkaido Univ. Ser. 7* **3**, 379 (1971).
25. S. Murauchi and W. Ludwig, *Initi. Rep. Deep Sea Drill. Proj.* **56-57**, 463 (1980).
26. R. N. Anderson and M. D. Zoback, *ibid.*, in press.
27. A. B. Watts, J. K. Weissel, R. L. Larson, *Tectonophysics* **37**, 167, (1977).
28. T. Wantanabe, M. G. Langseth, R. N. Anderson, in *Island Arcs, Deep Sea Trenches and Back Arc Basins*, M. Talwani and W. Pitman, Eds. (American Geophysical Union, Washington, D.C., 1977), pp. 137–161.
29. M. E. Chapman and M. Talwani, *Geophys. J. R. Astron. Soc.*, in press.
30. C. G. Chase, *Nature (London)* **282**, 464 (1979).
31. M. Ewing and B. C. Heezen, *Science* **131**, 1677 (1960).
32. H. H. Hess, in *Petrologic Studies: A Volume in Honor of A. F. Buddington*, A. E. J. Engels *et al.*, Eds. (Geological Society of America, New York, 1962), p. 599.
33. F. J. Vine and D. H. Mathews, *Nature (London)* **199**, 947 (1963).
34. X. LePichon, *J. Geophys. Res.* **73**, 3661 (1968).
35. J. R. Cann, *Geophys. J. R. Astron. Soc.* **15**, 331 (1968).
36. M. G. Langseth, X. LePichon, M. Ewing, *J. Geophys. Res.* **71**, 5321 (1966).
37. J. B. Corliss *et al.*, *Science* **203**, 1073 (1979).
38. J. T. Wilson, *Nature (London)* **207**, 343 (1965).
39. B. C. Heezen, M. Tharp, M. Ewing, *Geol. Soc. Am. Spec. Pap. 65* (1959).
40. A. S. Laughton and R. C. Searle, in *Deep Sea Drilling in the Atlantic Ocean: Ocean Crust*, M. Talwani, C. G. Harrison, D. E. Hayes, Eds. (American Geophysical Union, Washington, D.C., 1979), pp. 15–32.
41. R. Hey, *Geol. Soc. Am. Bull.* **88**, 1404 (1977).
42. J. A. Orcutt, B. L. N. Kennett, L. M. Dorman, *Geophys. J. R. Astron. Soc.* **45**, 305 (1975).
43. A. W. H. Bunch and B. L. N. Kennett, *ibid.* **61**, 141 (1980).
44. R. E. Houtz, *Geol. Soc. Am. Bull.* **91** (Part 1), 406 (1980).
45. T. J. Herron, W. J. Ludwig, P. L. Stoffa, T. K. Kan, P. Buhl, *J. Geophys. Res.* **83**, 132, (1978).
46. T. J. Herron, P. Stoffa, P. Buhl, *Eos* **61**, 367, (1980).
47. F. M. Richter, *J. Geophys. Res.* **78**, 8735 (1973).
48. A. B. Watts, J. H. Bodine, N. M. Ribe, *Nature (London)* **283**, 532 (1980).
49. C. R. B. Lister, *Geophys. J. R. Astron. Soc.* **39**, 465 (1974).
50. R. N. Anderson, M. G. Langseth, J. G. Sclater, *J. Geophys. Res.* **82**, 3391 (1977).
51. J. M. Edmonds, *Eos* **61**, 129 (1980).
52. R. N. Anderson, M. A. Hobart, M. G. Langseth, *Science* **204**, 828 (1979).
53. CRRUST (Costa Rica Rift United Scientific Team), in preparation.
54. K. D. Klitgord and J. C. Behrendt, *Mem. Am. Assoc. Pet. Geol.* **29**, 85 (1979).
55. J. I. Ewing and M. Ewing, *Geol. Soc. Am. Bull.* **70**, 291 (1959).
56. R. E. Sheridan, J. A. Grow, J. C. Behrendt, K. C. Bayer, *Tectonophysics* **59**, 1 (1979).
57. P. L. Stoffa, P. Buhl, T. J. Herron, T. K. Kan, W. J. Ludwig, *Mar. Geol.* **35**, 83 (1980).
58. Lamont-Doherty Geological Observatory contribution No. 3168. This manuscript was reviewed by A. B. Watts, W. Pitman, and P. Rabinowitz. The GLORIA data from R. Searle in the SEABEAM map from V. Renard were kindly made available prior to publication. This work was supported by NSF grants DPP80-19461 and OCE 80-19452.

Crustal Processes of the Mid-Ocean Ridge

East Pacific Rise Study Group

In 1854, Matthew Fontaine Maury published the first bathymetric chart of the North Atlantic Ocean, revealing the presence of a great ridge running down its central axis (*1*). Thought at that time to be a geosynclinal structure, the Mid-Ocean Ridge (MOR) has proved to be the largest single geological feature on the surface of the earth. Stretching for a distance of 72,000 kilometers and circling the globe, it covers over 28 percent of the planet's surface.

During the last quarter century, the MOR has assumed considerable importance in geological thought, particularly in the development of modern concepts of global tectonics. We now understand it as a site of mantle upwelling along which the lithospheric plates of the oceans develop. Until recently, the study of this great geologic province took place along several parallel but separate lines of inquiry, each focusing on different aspects of the ridge system: its surficial volcanism, heat budget, magnetic character, isostatic response, hydrothermal activity, crustal structure, suspected composition, and subbottom crustal processes. Within the last few years, however, these parallel studies have begun to converge on a central question: What is the nature of the magma chamber system that underlies the MOR and is thought to be responsible for the observed processes? What follows is a summary of these separate lines of evidence and a synthesis that attempts to present a unified model of the magma chamber system and its related crustal processes, the chemistry of the ocean itself, and the occurrence of massive sulfide deposits in the rifted central axis.

The members of the group (listed alphabetically) are as follows: Robert D. Ballard, Ocean Engineering Department, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543; Harmon Craig, Scripps Institution of Oceanography, La Jolla, California 92093; John Edmond, Department of Earth and Planetary Sciences, Massachusetts Institute of Technology, Cambridge 02139; Marco Einaudi, Department of Applied Earth Sciences, Stanford University, Stanford, California 94305; Robin Holcomb, U.S. Geological Survey, Vancouver, Washington 98663; Heinrich D. Holland, Department of Geological Sciences, Harvard University, Cambridge, Massachusetts 02138; Clifford A. Hopson and Bruce P. Luyendyk, Geology Department, University of California, Santa Barbara 93106; Kenneth Macdonald, Department of Geological Sciences, Marine Science Institute, University of California at Santa Barbara, Goleta 93106; Janet Morton, Geophysics Department, Stanford University; John Orcutt, Scripps Institution of Oceanography; and Norman Sleep, Geophysics Department, Stanford University.

Gravity Structure and Seismology of the Mid-Ocean Ridge

A decade ago Dorman and Lewis suggested that the relationship between gravity and topography could be computed as a function of spatial wavelength (*2*). This technique was subsequently applied to investigations of ocean basins. Cochran (*3*) applied it to various segments of the MOR and concluded that (i) an elastic plate model which supports the topograpic load partly through flexural strength is required; and (ii) the plate thickness of the East Pacific Rise (EPR) is 2 to 6 km and that of the Mid-Atlantic Ridge (MAR) is substantially larger, 7 to 13 km. There are, however, some questions about whether on the basis of gravitational field data it may be possible to resolve this difference. In spite of these questions, the results are consistent with the idea that the lithospheric plates cool and thicken with time as they move laterally away from the spreading center.

Theoretical models of the temperature distribution near the ridge axis are in general agreement with the conclusions from gravity data. One can calculate the temperature in the region of the ridge axis by solving the vertical heat flow equation for steady-state emplacement and horizontal displacement away from

 0036-8075/81/0703-0031$02.00/0