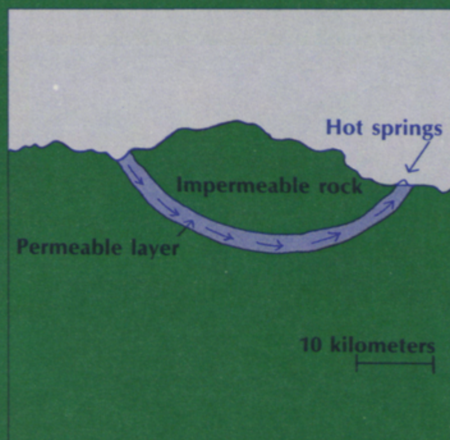
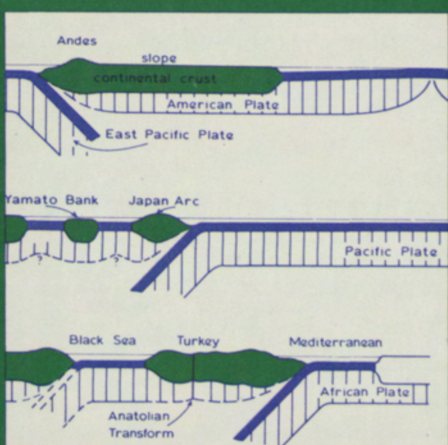
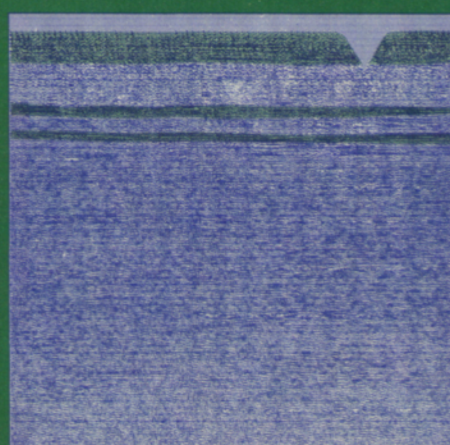
ENGINEERING

CORNELL QUARTERLY

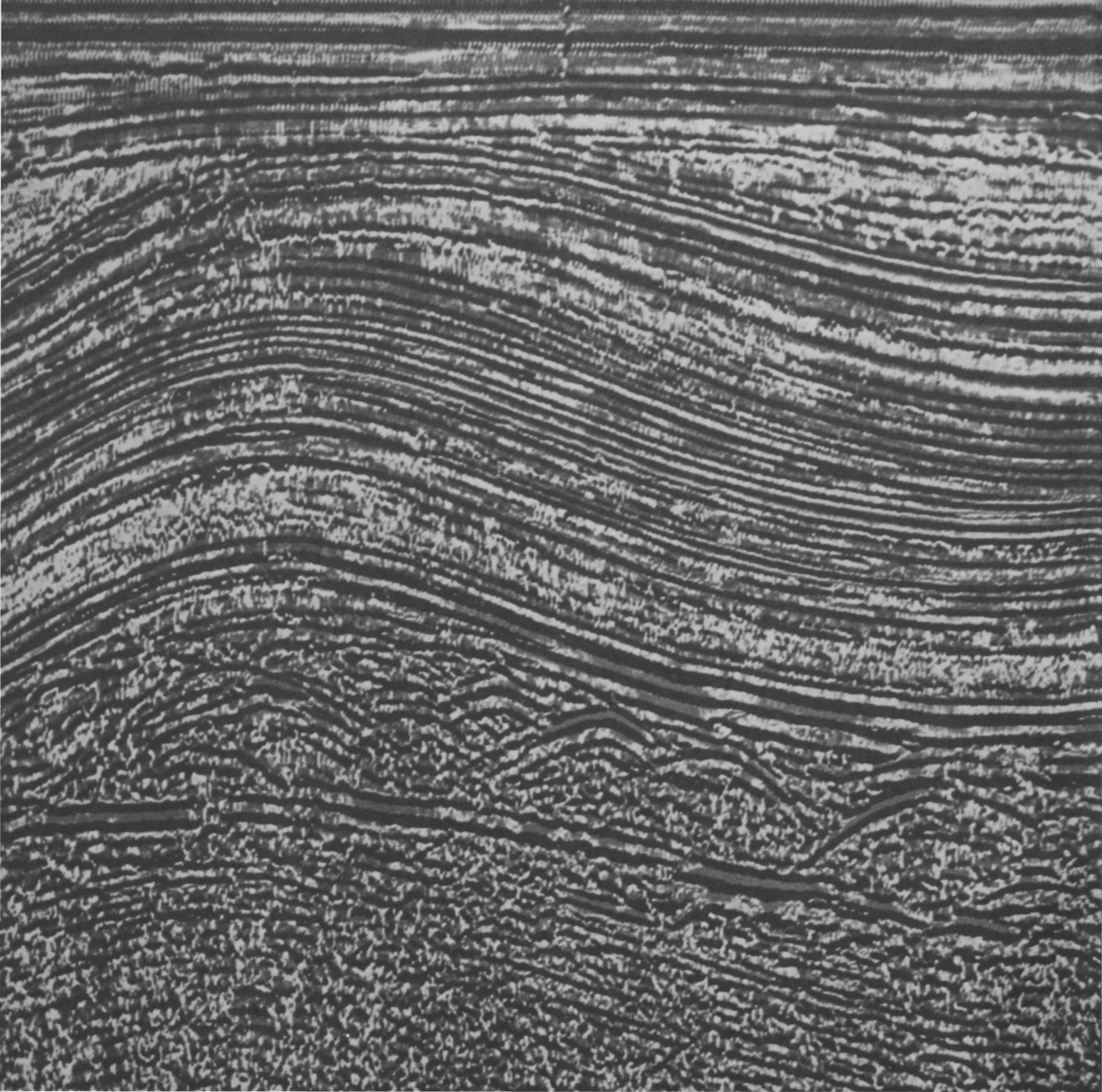






VOLUME 11
NUMBER 1
SPRING 1976

PROSPECTING WITH GEOPHYSICISTS



IN THIS ISSUE

Seismic reflection profiling is the technique used in an ambitious cooperative study of the earth's deep crust and upper mantle. Sidney Kaufman, professor of geological sciences, discusses the method, its scientific and economic potential, and some preliminary results.

John M. Bird, professor of geological sciences, explains how plate tectonic models have led to a new understanding of the genesis of ore deposits and may help in efforts to locate them. His particular interest is in the origin of ore bodies in mountain belts.

Field studies on an Indonesian arc island are part of a Cornell study of marine geologic processes. The research and its implications are discussed by Daniel E. Karig, associate professor of geological sciences.

The prospect of tapping new sources of geothermal energy has provided impetus to research into the complex processes that occur in geothermal areas. Donald L. Turcotte, professor of geological sciences, considers both scientific and economic aspects of current research in this field.

A Cornell research group headed by Arthur F. Kuckes, professor of applied physics, is studying electrical conductivity in the earth's deep crust, an indication of geothermal activity.

Engineering: Cornell Quarterly, Vol. 11, No. 1, Spring 1976. Published four times a year, in spring, summer, autumn, and winter, by the College of Engineering, Cornell University, Carpenter Hall, Campus Road, Ithaca, New York 14853. Second-class postage paid at Ithaca, New York. Subscription rate: $4.00 per year.

Opposite: A seismic profile, showing reflections and diffractions, of a geologic structure in southern Texas, from ground surface to a depth of about ten kilometers. (Courtesy of Seiscom Delta, Inc.)

EXPLORING THE EARTH'S BASEMENT

by Sidney Kaufman

A little known region of the earth—the deep continental crust, as much as sixty kilometers beneath the surface—is being explored in a cooperative project headed by Cornell geophysicists. It is a study with both scientific and economic potential, for the rocks of the basement may hold vital clues to such questions as how the continents were formed, what processes account for the geological features we presently observe, how the origin and history of sedimentary basins can be explained (an important question of the petroleum industry), and how the underlying causes of concentration and placement of minerals can be understood (an important question of the mining industry).

The study of a region so far underground, too deep for drilling, must be done indirectly with the use of sophisticated geophysical techniques. We are using the continuous seismic reflection method, a powerful technique developed for use by the petroleum industry to investigate the shallower sedimentary layers where oil is found. We are adapting the method to studies of the deeper crust and upper mantle, with the goal of obtaining well-defined profiles of important geologic structures. We have demonstrated that horizons can be traced at depths up to thirty or forty kilometers, and that even deeper zones can be characterized.

THE PROJECT IDEA AND HOW IT DEVELOPED

The project is conceived as a series of studies in selected areas of the continent, chosen so that the results, if successful, would have an important impact on geological thinking. The first phase of the work, two short projects to test the feasibility of the method, has now been successfully completed and plans for full-scale geological studies are under way. Each of the two tests consisted of short profiles with a total length of about thirty-seven kilometers. The first location was in Hardeman County, Texas, and the second was in the Rio Grande rift region in the southern part of the Albuquerque basin in New Mexico. Although the area covered in each test was relatively small, an abundance of high-resolution and meaningful data was obtained, verifying that the method does present data that does indeed offer a strong advance in observational seismology.

The deep reflection profiling project is a part of the United States program for the International Geodynamics Project, in which fifty-two countries currently have national programs. The international effort is designed to promote research on the dynamics and the dynamic history of the crust of the earth, an area of knowledge that has assumed great importance as a result of recent work in plate tectonics. The fundamental concept of plate tectonics, which depicts the foundation of the earth's surface as a composite of plates moving with respect to each other, has revitalized the earth sciences by providing a unifying basis for previously fragmented information. In addition, it has revealed many opportunities for studies that would have an impact on our thinking about problems connected with the exploitation of the earth's resources.

The United States program was organized by the Geodynamics Committee of the National Academy of Sciences, which defined six "high priority" subjects to be studied. Our project, one of the defined subjects, is a study of the fine structure of the crust and upper mantle. It is being conducted by the Consortium for

". . . a study with both scientific and economic potential"

Continental Profiling (COCORP), which consists of representatives from five universities—Cornell, Houston, Princeton, Texas, and Wisconsin—and one oil company, Shell. Operational responsibility is delegated to our group at Cornell, with Jack E. Oliver serving as chairman and myself as executive director. The project is funded by the National Science Foundation (NSF).

This research is drawing attention from a wide variety of individuals and organizations with expertise, experience, and interest in its various aspects. A result is an unusual blending of the efforts of participants from industry, government, and universities; for example, our advisory committees on site selection and on technical procedures include scientists from all these sectors. The NSF grant stipulates that any academic institution, government agency, or industrial group doing research on the structure of the solid earth is eligible to participate in the project and receive information developed by COCORP. All participants in the United States Geodynamic Project are kept informed of the status of the research, and the seismic data are freely available. We have already received more than one hundred fifty requests from all over the world for project information; some forty correspondents have ordered copies of the seismic sections and reels of magnetic tapes. (The copies are furnished at the cost of reproduction, of course.) We believe that the high level of cooperation, interaction, and exchange of information is an important factor in the progress of the project.

FINE CRUSTAL STRUCTURE AND ITS SIGNIFICANCE

The idea of studying basement rocks by continuous reflection profiling is not new. Previous investigative studies, mostly in Europe, have demonstrated that the method can be productive, at least in certain places. But the technique has not been used systematically in the United States, and has not previously been developed to its full potential for the kind of investigation we are undertaking.

Determination of structure by the tracing of reflecting horizons is a method widely used in the petroleum industry. However, interpretations of geologic structure based on the character of reflections, or on the buried foci hypothesis, are less frequently used in the seismic exploration of the sedimentary layers. These methods are likely to be much more prominent in exploration of the deep basement, where continuous reflectors are less common and focusing reflectors are more likely to be found. While the basic principles are the same, interpretation of seismic data from the deep basement will, on occasion, stress phenomena different from those commonly emphasized in the exploration of sedimentary rocks.

One of the questions we hope to resolve concerns the nature of rock emplacements in the earth's crust. The Mohorovicic (Moho) discontinuity, often depicted as the boundary between the crust and upper mantle of the earth, has been detected in many places around the world by means of refraction seismology. But our reflection results suggest that the layering is not completely continuous, and that there may be other, less defined, discontinuities. If this is so, the implications for geological history are significant, for it would imply a more complex process for the evolution of the continental crust from the primitive mantle. At any rate, new knowledge about the character of the crust would greatly help in formulating a theory of crustal differentiation.

Information on the basement is also potentially valuable in understanding the nature and history of the sedimentary basins. Knowledge of the deeper structures could shed light on problems of data interpretation encountered by geologists and geophysicists who are primarily concerned with the oil-bearing sedimentary layers. Likewise, the search for mineral deposits associated with certain structural features of the basins—major faults or intrusions, for example—will be aided by information on deep structure, and the method could be useful in the search for, and evaluation of, potential sites for extraction of geothermal energy. Surely, deep drilling into the basement for scientific or economic purposes should be preceded by seismic exploration of the drilling site and the surrounding region.

THE TECHNIQUE OF SEISMIC REFLECTION PROFILING

A number of seismic methods may be used for exploration of the earth's crust. They include seismic refraction, which reveals gross structural features; wide-angle reflection; and methods based on body-wave travel time anomalies, body-wave spectra, and surface-wave dispersion. The advantage of the method we are using is that it can reveal features in much greater detail; it represents a technical advance analogous to the development of a telescope with much greater resolving power. Our preliminary results suggest that the emphasis in exploration of the continental basement will shift from seismic refraction techniques to seismic reflection methods, as has occurred both in petroleum exploration and in studies of the deep-sea floor.

The principle of seismic reflection profiling is basically that of the simple echo system. A signal is introduced at the surface, either by exploding a charge or by shaking the ground, and reflections from subsurface layers are recorded over a period of time. The time of travel of the reflected signals is a measure of the depth of the reflecting layers. The sources and the receivers are moved along the ground so that a nearly continuous profile of the subsurface is obtained.

GENERATING SEISMIC WAVES WITH A LARGE VIBRATOR

In our field tests we used the VIBROSEIS technique, a development of the Continental Oil Company, which generates seismic waves by shaking the ground with a large truck-mounted vibrator. Commonly, several vibrators operate synchronously in the field. The method has several advantages over explosive techniques: shot holes are not required and operation in populated areas is feasible, the frequency spectrum can be controlled, and the signal-to-noise ratio can be effectively improved by direct summation of a number of vibrator sweeps. There are, however, practical limits to the number of vibrator sweeps that can be summed and, therefore, to the improvement of the signal quality; under conditions in which large source energies are required, it might be preferable to use explosive sources.

The system for generating the seismic waves consists of a number of truck-mounted vibrators that are positioned so as to form a prescribed source array. The form of the signal imparted to the ground is that of a chirp, a near-sinusoidal wave train whose frequency changes gradually through the duration of the signal. The method is exactly analogous to certain radar methods and has the same advantage: a better signal-to-noise ratio is obtainable by suitable processing of the observed data.

The basic element of the receiving system is the geophone, a compact, rugged seismometer. Many geophones are grouped together in some determined configuration to form a receiver array, and a number of such arrays constitutes a spread. We used twenty to thirty geophones in each array and forty-eight arrays in a single spread. The ground position at which a geophone array, or a source array, is centered is called a station; stations are normally equally spaced along the profile line.

Getting good information depends on effective design of the source and receiving systems and on effective handling of the data. For example, the configuration and dimensions of the receiving spread must be designed to enhance detection of the near-vertical signals and minimize the effect of other signals, particularly those traveling horizontally. Recordings somewhat off-vertical must be obtained to provide information on velocity structure that is needed to convert the time scale to one of depth. The signals from repeated vibrator sweeps are summed in the field; the

Left: Truck-mounted vibrators such as this were used in the COCORP seismic reflection profiling project in Texas. The truck is shown in operating position, with the rear wheels elevated and the pad in contact with the ground. As the truck vibrates, the energy is transmitted to the earth, generating seismic waves.

Above: Trucks line up to take their positions along the line of stations. The placement of the vibrators is among the field parameters that must be established for each series of measurements.

Left: The hood of an automobile serves as a desk for researchers determining the required field parameters. Left to right: Fred Barr of Petty-Ray, Inc.; Milton Dobrin of the University of Houston, a member of the COCORP executive committee; Cornell's Sidney Kaufman; and Harry Mayne of Petty-Ray.

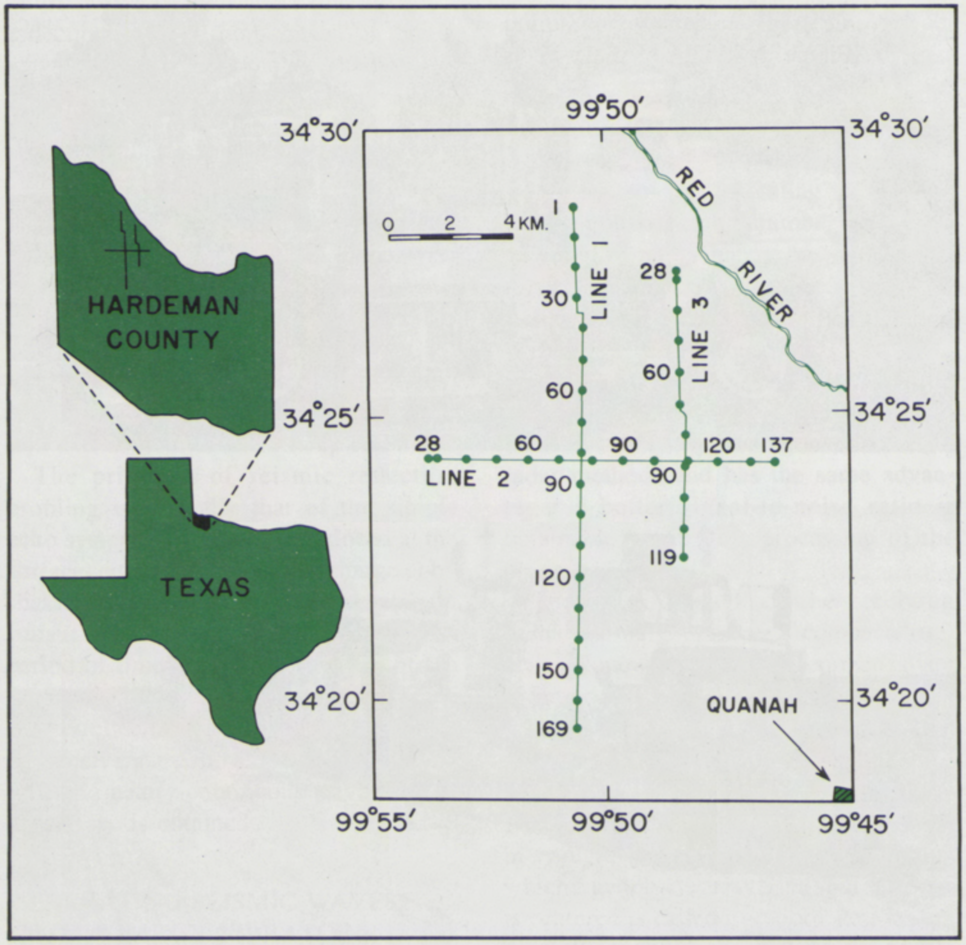
correlation process and further signal processing is done in the computation center. During processing, the signal-to-noise ratio is further improved by a process called common depth point stacking (CDP), which is a way of combining rays incident at different angles upon a particular point of a reflector.

It is apparent that although the principles of seismic reflection profiling are straightforward, its application is complicated and sophisticated. Moreover, the data are complex and amenable to various kinds of processing and interpretation, so that the analysis is not completed in one step. Nevertheless, a substantial amount of valuable information is available at first brush, and preliminary conclusions must be made in order to guide the later processing.

THE FIRST FIELD WORK IN HARDEMAN COUNTY, TEXAS

The first task of our test project was to select sites for the initial field work. Information already available—a limited amount from previous reflection studies of the basement, extensive data from the oil companies' measurements of sedimentary

Figure 1. The locations of Hardeman County and of the test site. Stations along lines 1, 2, and 3 are indicated.



layers, and observations of surface outcrops of basement rocks—suggested that some sites would be more interesting and productive than others. A committee of fourteen members from oil companies, university geology departments, and government agencies reviewed possible sites, considering them from the standpoints of both reflection quality and geological interest. The Hardeman County basin area was selected for the first tests, partly on the basis of data collected by a number of major petroleum companies who are cooperating in our project by extending the measurements they take during normal field operations. As it turned out, both good reflectors and interesting geology were encountered in Hardeman County.

Because much equipment and expertise is needed to make the kind of measurements needed for a project of this sort, the field and computational work was done by a geophysical contracting company, Petty-Ray, Inc., of Houston. With five synchronized vibrators, a battery of geophones, and a 48-channel data-acquisition system, the professionals were able to accomplish in three weeks what could have been done by, say, two professors and six students in several years. Of course, the project provided valuable instructional opportunities for students; for example, teams from several of the participating universities brought instruments to the site and "piggybacked," making separate recordings of the generated signals. Also, the information is useful for classroom study of the theory of seismic reflection profiling and will be the basis for many advanced research projects.

The basic procedure was to modify techniques normally used in geophysical prospecting for oil to obtain data from the deeper structures. A difference was that the time length of the records was extended from the usual six seconds or less to fifteen or twenty seconds. Before production work started, several days were spent in establishing the field parameters, including the placement of vibrator and geophone arrays and the vibrational signal frequencies to be used. The stations were spaced one hundred meters apart, with vibrators located at every other station. Twenty-four geophones per station were spread over a distance of two hundred meters, so that there was complete overlapping of receiving units from adjoining stations. Figure 1 is a plan of the lines run in Hardeman County.

WHAT CAN WE LEARN FROM THE TEST DATA?

An example of the data obtained is shown in Figure 2, which is a time section corresponding to line 1 of Figure 1. Such a section contains a great quantity and variety of information of interest to those willing to take the time to study and interpret it.

Let us consider Figure 2 in some detail to discover what information is available. The horizontal scale is distance, a total of about 16.6 kilometers, with stations every one hundred meters. The vertical scale is two-way travel time to fifteen seconds, which corresponds to a depth of about forty-five kilometers. The section is made up of many vertical, wiggly line traces at half-station intervals, each with the half-cycle to the right of center blacked in. Correlation by eye reveals lineups, or places where half-cycles of the same polarity can be followed more or less horizontally through many adjoining traces. These are indications of reflecting surfaces.

From the beginning of the section to a time of about 1.6 seconds, a number of near-horizontal reflectors that are more or less continuous across the profile are evident. This group of reflectors corresponds to the sedimentary section; since this is the only part of the data related directly to potential petroleum reservoirs, almost all previous seismic reflection profiling has been focused on this region. It is, however, the region below 1.6 seconds—the basement, containing igneous rocks—to which our study is directed. Processing of these data was designed specifically to enhance information in this lower part of the section.

Below the basement surface (at 1.6 seconds), for an interval of about one second, there is a zone almost devoid of reflectors. This zone must be transparent rather than opaque, for detection of deeper reflectors demonstrates that energy has penetrated it. From about 2.8 to 3.0 seconds, and again from 3.6 to 4.0 seconds, there are strong reflectors that can be followed throughout the length of the profile. Some structure can be seen in these reflectors. The lower one, for example, has a synclinal form and also shows offsets—between stations 50 and 80, for example—that may be indicative of faulting. Careful study of the record (viewing it from a low angle is helpful) will reveal much more complexity. There is good evidence for unconformities, or interfaces between layers of different geological age, beneath both of these strong, continuous reflectors; such information is particularly important in attempting a correlation with a geological section, and it also provides information on the nature of the reflecting horizons. At times greater than 4.0 seconds, a practiced observer can detect a great deal of information of various kinds, including strongly dipping diffractions as well as the horizontal and near-horizontal lineups. The relatively long horizontal reflections appear in a background of shorter and more common bands of reflections, and are often grouped.

DISTINGUISHING ZONES IN THE BASEMENT ROCK

There are portions of the seismic reflection sections where groups of reflectors have common characteristics that distinguish them from their surroundings. These characteristics include the density of reflectors and also the velocities (determined in separate measurements) with

"...an understanding of earth structures and dynamics is basic to advances in such areas as earthquake prediction and the location of resources."

which seismic waves travel through a zone. Using such features it is possible, somewhat in the manner of a geologist mapping unknown terranes, to construct a section displaying different zones. An example, corresponding to the Hardeman County data of Figure 2, is shown in Figure 3. Drawing such a section involves some interpretation and generalization, but it seems an appropriate step to test the potential of the seismic profiling method.

Interpretation of the layers depicted in Figure 3 depends on correlation with geologic information, very limited at the present time, on the basement rocks of the region. One plausible interpretation is that layer A is mostly granite, layer B corresponds to marine igneous rocks, and layer C is metamorphosed sedimentary rock with granite intrusions. Among the interesting features that show up still lower in the crust, are lineups that show curvature rather than the usual horizontal alignment. One possible interpretation of this phenomenon is the presence at great depths of broad, fold-like structures, similar to certain exposed rock structures that some geologists believe were once at lower crustal depths.

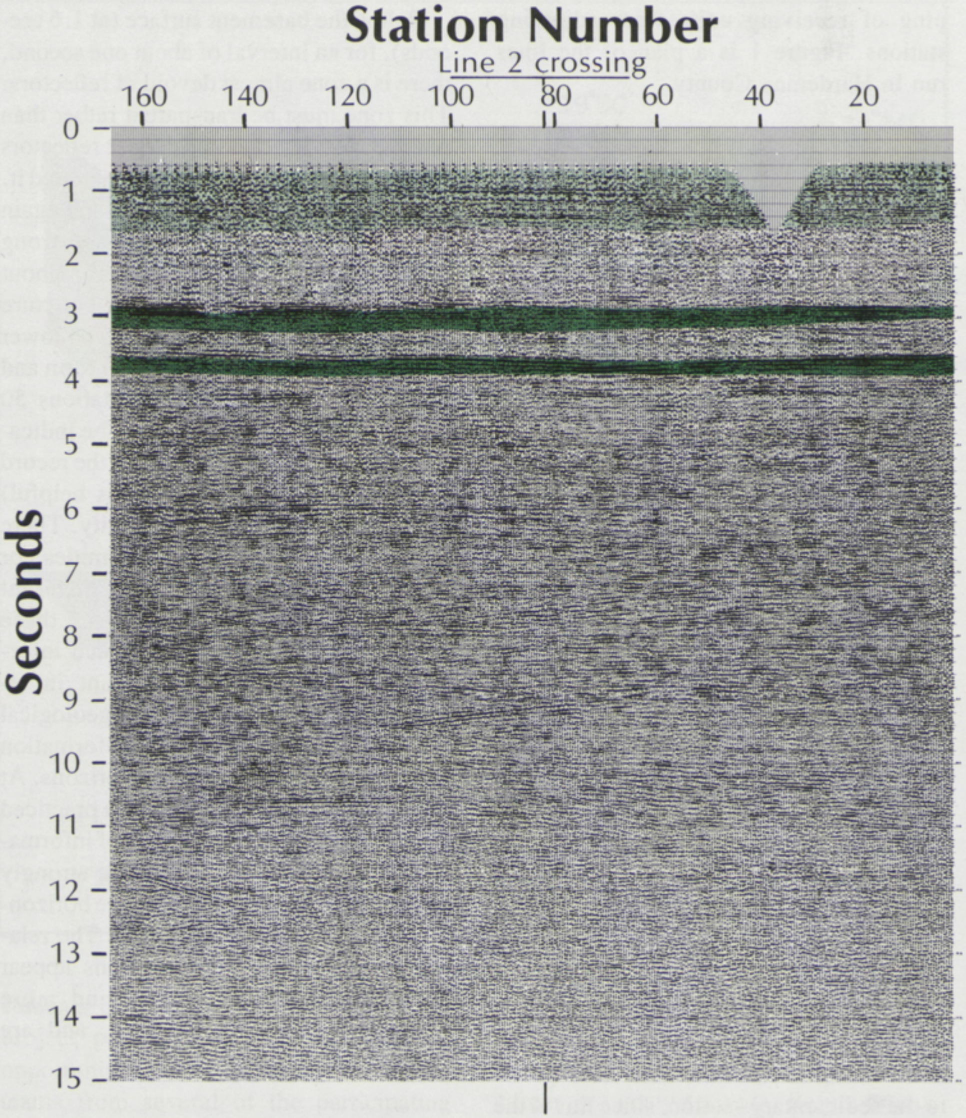


Figure 2. A record section of the seismic reflection profile of line 1 of Figure 1, a location in Hardeman County, Texas. The horizontal scale represents distance along the surface, and is numbered by stations situated one hundred meters apart to make a total length of 16.6 kilometers. The vertical scale is two-way travel time in seconds, corresponding to depths as much as 45 kilometers beneath the surface of the earth. The upper part of the section, at times usually less than one second, but including the V-shaped area near station 38, is of little significance in the present study. The sedimentary layer, where oil is found, extends only as deep as about 1.6 seconds, and below that is the crystalline rock of the crust. Dark horizontal markings indicate reflecting surfaces. A geological interpretation of these data is illustrated in Figure 3.

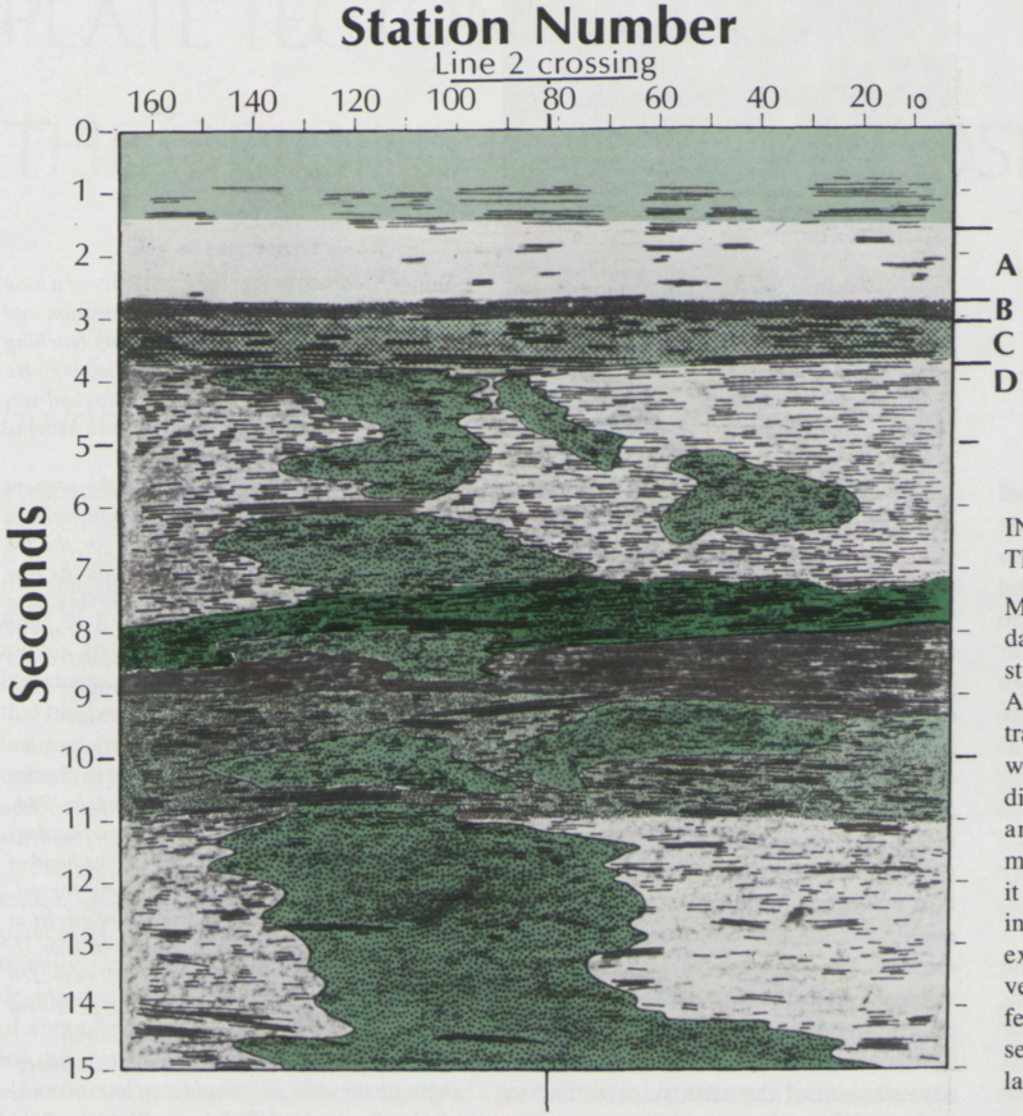


Figure 3. A section of crust showing zones of rock with common characteristics. This drawing summarizes information and indications derived from the seismic reflection data of Figure 2, and the layers A, B, C, and D correspond to zones identified in that record. The markings used to distinguish the different zones have no lithographic connotation. The zones are characterized from each other by the density of reflecting surfaces and by the velocities with which the seismic waves travel through them. Approximate thicknesses are A=3.5 kilometers, B=0.5 to 1.0 kilometers, and C=2.5 kilometers. Layer D has no clear lower limits. Although the differences between the irregularly shaped bodies in layer D are readily apparent in the original records, there is some uncertainty in fixing their boundaries. A preliminary interpretation of these bodies is that they are igneous intrusions younger than the surrounding rocks. Although this project did not attempt to detect and map the major discontinuity known as the Mohorovicic (Moho), it is possible that reflections at or below 11 seconds might be identified with it.

INFORMATION THAT FURTHER TESTING MAY REVEAL

More reliable interpretation of the seismic data will be possible with further geologic study of the basement rocks in the region. Alternately, the seismic horizons could be traced by subsequent profiling to locations where the basement is well known. In addition, refinements in processing the data and the use of different processing methods for different purposes may make it possible to extract considerably more information from the measurements. For example, better determinations of the velocities of the seismic waves in the different layers should result in better assessments of the depth and thickness of the layers.

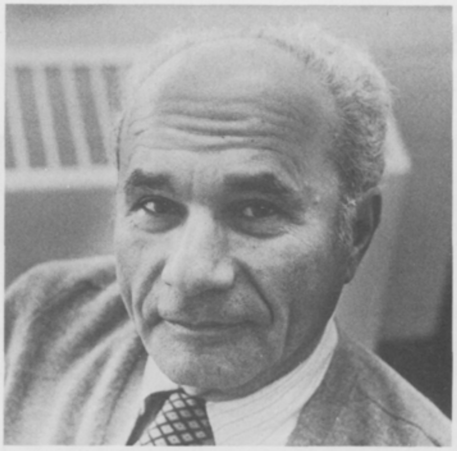
It also appears that information can be obtained from even greater depths than we explored in our preliminary tests. When data are processed by a method that preserves information on the amplitudes of reflections, as was done with part of our Hardeman County data, it is clearly seen that amplitude falls off rapidly in the sedimentary layers but slowly in the deeper layers. Once seismic energy is in the basement, it apparently propagates very efficiently. In subsequent experiments, longer recording times may yield information about depths well into the mantle.

THE POTENTIAL OF EXPLORATORY REFLECTION SEISMOLOGY

We chose reflection seismology as the technique for our large-scale project because we believe it is the best available for our scientific purposes. It makes an exciting project, for such deep seismic reflection profiling is a method still in the developmental stages, when the work is most interesting and potentially useful.

This choice also carries a benefit for university educational programs, for the results are made available for study. In the past, the universities have tended to emphasize other geophysical techniques, such as those involving measurements of gravity or magnetism, that cost less to employ or are more easily taught. Now students will have more opportunity to study a seismic technique that promises to become increasingly important.

In addition to the scientific and educational value of this project, there are possible practical benefits, for an understanding of earth structures and dynamics is basic to advances in such areas as earthquake prediction and the location of resources. This aspect of the research enhances its appeal and adds to its value, for every worthwhile study, however "pure," bears some relation to ultimate applications; there is no real distinction between basic and applied research, except perhaps in attitude and approach. Continuous seismic reflection profiling applied to the deep crust promises to contribute substantially both to the advancement of the earth sciences and to their usefulness.



Sidney Kaufman brings the experience of a long career in industrial petroleum exploration and production research to his university teaching and research in geophysical prospecting. He became a Cornell professor of geological sciences in 1974, after thirty-seven years with the Shell Development Company.

His major research activity at the present time is the seismic reflection profiling work, a part of the United States program for the International Geodynamics Project, that he discusses in this article. He is also serving as a consultant on geothermal energy to the Energy Research and Development Administration (ERDA) and to the Lawrence Livermore Laboratory of the University of California.

Kaufman received his university education at Cornell, earning the A.B. degree in physics in 1930 and the Ph.D., also in physics, in 1934. After a two-year period at Cornell as a postdoctoral fellow, he joined Shell in 1936 as head of a geophysical field crew prospecting for oil. Subsequently he served as a radar physicist in the United States Navy during World War II, returning to Shell as senior staff research physicist and assistant to the vice president for exploration and production research.

His professional activities include memberships in the advisory council of the Institute of Geophysics and Planetary Physics of the University of California, the committee on seismology and the joint panel on seismology and rock mechanics of the National Academy of Sciences, and the earthquake hazards review panel of the United States Geological Survey. He is a member of the Society of Exploration Geophysicists, the Seismological Society of America, the American Geophysical Union, the American Association for the Advancement of Science, and Sigma Xi.

PLATE TECTONICS AND THE ORIGINS OF ORE DEPOSITS

by John M. Bird

Prospecting for mineral ores has developed largely on the premise that "gold is where you find it." But recently a key to the genesis and, perhaps, the location of most of the major accessible reserves of metals and other resources has been taking shape. It lies in a model of the earth that has been assembled by geologists over the past ten years or so to form the first cohesive picture of the geologic history and continuing evolution of our planet's surface.

The model, called lithosphere plate tectonics, shows that approximately seventy percent of the surface of the earth is continually "cycled" by the generation and destruction of surface area, over intervals of about four hundred million years. During this cycling, the surface of the planet is also affected mechanically and chemically by the motions and interactions of water and atmosphere, driven by solar energy impinging on the planet (see Figure 1). Essentially, the surface undergoes an inexorable progression of morphological, geographical, and chemical changes as a consequence of the action of two energy sources—the sun and the earth's hot interior. During the course of geologic evolution, these two "heat engines" generate—and later change—the rocks and minerals that constitute the material base for technology. "Ores" and "fuel reserves" are economic manifestations of these occurrences.

As metal-based industry developed, mining technology advanced rapidly. Discovery of ore bodies, however, has been made largely through the trial-and-error endeavors of prospectors. The old conceptual model of a static earth did little for our understanding of the how and wherefore of the origins and distributions of ores; for the most part, only ore bodies at or near the surface of the continental land regions have been found and exploited. Now, however, the framework of plate tectonic models has led to a new understanding of ores on a global basis and has provided a great thrust to our efforts in locating them.

WHAT PLATE TECTONICS TELLS US ABOUT THE EARTH

The outer "shell" of the earth, varying in thickness from as little as five kilometers to as much as two hundred kilometers, is called the lithosphere. Continents "sit" within the lithosphere as huge, buoyant "islands" of granite-like rock called continental crust. Most of the lithosphere is mantle rock called peridotite, covered with an approximately five-kilometer layer of rock called basalt, which is the material of the oceanic crust.

Within the oceans are great mountains and depressions, called ridges and trenches. Detailed mapping and analysis of these features show them to define the boundaries of segments of lithosphere. We now know that the apparently rigid outer shell is in fact a mosaic of spherical caps of lithosphere, all in motion relative to one another.

MAGNETIC ANOMALY STRIPES: RECORD OF GEOLOGIC HISTORY

The evidence for this motion comes from studies of the magnetic properties of the sea-floor rocks along the oceanic ridges that circle the globe. The system of ridges extends from the Arctic through the Indian Ocean and into the Pacific, where it adjoins North America at the northern end of the Sea of Baja California; the segment known as the Mid-Atlantic Ridge separates North and South America from Europe and Africa. Magnetometer surveys of the ocean floors have shown that in the

Figure 1

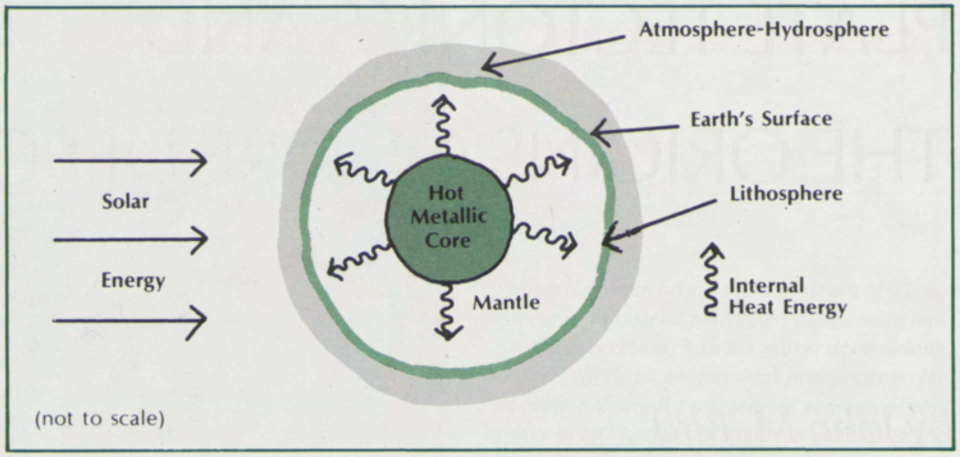


Figure 1. The two energy sources that bring about changes on the earth's surface, including the formation of mineral deposits. Solar heat drives atmospheric motion, which affects the surface mechanically and chemically through weather and erosion. Internal heat energy drives the movement of plates of lithosphere (crust and mantle), bringing about the generation and destruction of surface area at accreting and consuming plate margins. The concentration of minerals in ore bodies is a consequence of the plate tectonic and hydrospheric processes.

Figure 2

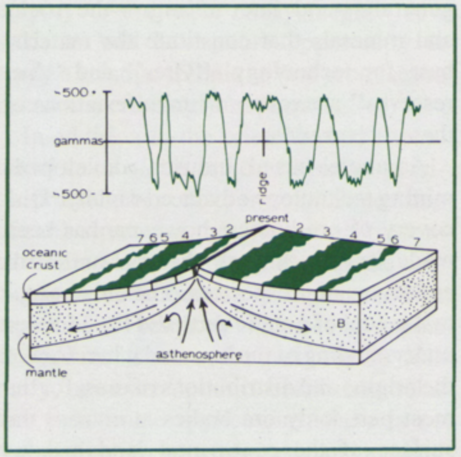


Figure 2. The evolution of plates as revealed by "magnetic anomaly stripes." The oceanic plates A and B separate at the accreting plate margin as molten material erupts from the earth's hot interior, solidifies, and adds new surface area along the marginal ridge. The stripes are magnetized regions in material that solidified during accretion. During crystallization, iron-rich minerals in the material align with the earth's magnetic field, and because the polarity of the earth's field periodically reverses, the direction of magnetism, as detected by magnetometer readings, also shows reversals. This record of lithosphere generation can be used to determine rates of accretion and the history of plate movements.

sea-floor rocks there are "stripes," symmetrically disposed about the ridges, that indicate alternating directions of the earth's magnetic field (see Figure 2). These stripes have recorded the magnetic direction because they are within rocks that have crystallized from molten lava: as the molten rock cools, early-formed magnetic minerals within the lava align themselves with the magnetic field of the earth. The recent revolution in the earth sciences commenced when it was recognized that these "magnetic anomaly" stripes are a "tape recording" of the generation of new surface area at the ridges. This is because, fortuitously, the magnetic field of the earth goes through episodes of polarity reversal—that is, the magnetic field episodically undergoes reversal of the north and south poles by collapse and regeneration of the field. The presence of the magnetic anomaly stripes, along with the fact that lava continually erupts along ridges, means that new surface area is continually being generated along these accreting plate margins. It amounts to about a square mile per year for all of the ridges.

THE RETURN OF LITHOSPHERE TO THE EARTH'S INTERIOR

The magnetic anomalies of the oceanic crust also abut the trenches in the ocean floors. Because the stripes disappear into these plate boundaries, and because of information about directions of plate motion derived from analysis of earthquakes that occur along the trenches, we know that lithosphere is returned to the interior as well as accreted from it (see Figure 3). Some of the oceanic crust that is carried down on the lithosphere melts and returns to the surface to form the chains of volcanic islands, known as island arcs, that are found in association with the trenches. (This process is discussed elsewhere in this issue by Daniel E. Karig.) The Pacific Ocean, for example, is rimmed by a "ring of fire," the volcanic islands and volcanic mountains that lie along the great Pacific trenches. In a related process, the Andean Mountains have formed on the continental mass next to the trench, or consuming plate margin, that borders the western edge of the South American continent. They are the result of forces and volcanic eruptions associated with the descent of sea floor back into the interior of the earth.

GEOLOGIC EVENTS AT THE PLATE BOUNDARIES

By measuring the rate at which the magnetic anomaly stripes have been generated about the oceanic ridges, and by tracing these anomalies to the regions of trenches where the sea floor is being consumed, we can calculate the rate at which the ocean floor is being accreted and consumed. These calculations show that the ocean floors are completely "cycled" in about four hundred million years. Because the stripes are not distorted, we also know that the great spherical caps, or lithosphere plates, are rigid bodies torsionally, and that therefore the continents "drift" about on geographic tracks that are determined by the way the lithosphere plates evolve. This model of lithosphere plate evolution has confirmed the older concept of continental drift (although the movement is nothing like the aimless wandering implied by the term *drift*).

The model of lithosphere plate tectonics also accounts for the huge mechanical building processes that form ocean ridges, island arcs, and Andean-type mountains. By analyzing the magnetic signatures of opened oceans such as the Atlantic and the Indian, we can now show that the large mountain chains within continental regions of southern Europe and Asia—the Alpine-Himalayan system—resulted from the closing of the ancient ocean Tethys by plate consumption and the actual collision of the Indian continent with Asia (see Figure 4). And we can predict the imminent (geologically speaking) collision of Africa and Europe by the closing of the Mediterranean Sea, to form a Himalayan-type mountain belt.

A third kind of boundary is necessary in the kinematics of rigid spherical caps moving by accretion and consumption. It is a boundary of lateral motion along which there is no surface-area change. This type of margin, called transform, is best exemplified by the San Andreas fault of California, where an accreting plate margin, the East Pacific Rise, intersects the consuming plate margin of the western side of the North American plate. The resultant motion across the plate boundary has "torn off" the coastal ranges and is moving them northward with respect to the rest of California.

The relationships of features of the earth's plates are illustrated in Figure 5.

MINERAL CONCENTRATION IN THE TECTONIC PROCESS

What does all this have to do with the origin of ore bodies? The generation and consumption of lithosphere create what is becoming known as the "geostill." As melts cool along the oceanic ridges and volcanoes erupt behind the trenches in island arcs, minerals of economic value are deposited in favorable host rocks, either those of the island arc volcanoes or the volcanic rocks that make up the new sea floor generated along the oceanic ridges (see Figure 6).

An extrapolation of this basic process may be applied to the evolution of mountain belts, both Andean and Himalayan in type, that contain some of the world's largest known reserves of certain metals: the huge copper deposits of Peru and Chile, for example. These mountain chains are continent-based, in contrast to the ocean ridges and island arcs, and are the consequences of *tectonic* evolution of continental rocks at plate margins. Much of the search for ores is within these mountain systems. Although the mountain chains are exceedingly complex in both their rock composition and their spatial and temporal aspects, we now have the

"As melts cool along the oceanic ridges and volcanoes erupt behind the trenches of island arcs, minerals of economic value are deposited"

Figure 3

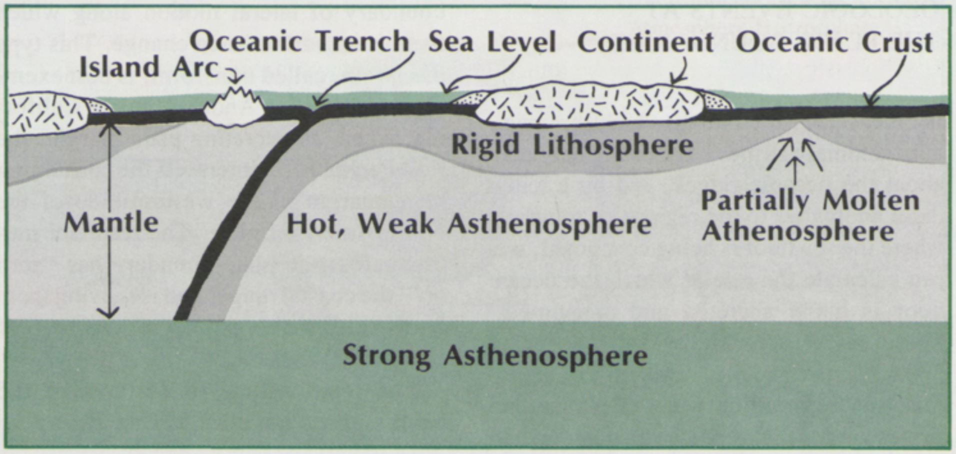


Figure 3. The tectonics of lithosphere plates. Partially melted material from the earth's interior emerges at an oceanic ridge along an accreting plate margin and solidifies to form new oceanic crust. The rigid lithosphere plate is gradually moved toward the consuming plate margin, where it slides under the adjoining plate and is subducted back into the interior. The consuming margin is marked at the surface by an oceanic trench and by a chain of island arcs, built by volcanic action resulting from the remelting of subducted crust. Any continental mass resting on the lithosphere is carried along by the plate movement, but because of its lower density, is not subducted. Discontinuities in the plates and underlying material are detected seismically.

possibility of better understanding their tectonics through our understanding of the construction and destruction of the oceanic lithosphere.

Another aspect of the geostill concept provides an explanation of the occurrence of large deposits of petroleum. Volcanic activity accompanying the subduction of lithosphere results in the formation of island arcs and contributes to the building of continental mountain chains. This volcanic material is incorporated into the continental crust and ultimately both are broken down and washed away as the mountains erode back down to sea level. The great amounts of sediment resulting from the erosion accumulate along continental margins or in basins within the continents—the sites of most of the world's petroleum.

CORNELL WORK ON A MODEL OF ORE GENESIS

Here at Cornell, graduate students are working with me on the development of a model of ore genesis in the context of the evolution of lithosphere plates as revealed by historical geology. A schematic showing the cycle of plates and the associated minerals (see Figure 7) was prepared by members of a graduate seminar during the 1975 spring term, and two students, William Rathke and Maura Weathers, are continuing this study for their doctoral theses. These students both hold fellowships provided by the Department of Health, Education, and Welfare for natural resources development, and the research is supported also by a National Science Foundation grant.

The model, although complex in detail and far from complete, shows that through an understanding of the evolution of oceans and mountain belts, the genesis of practically all of the world's known ore bodies can be better understood. Also, such studies promise to provide new insights in the search for additional ore bodies. An important element of the model is a mechanism for the generation of oceanic ridges. This is of great scientific interest, for it is the process by which much of the "permanent" rock of the surface—that is, the rock not returned to the interior—is generated.

From studies of the chemistry of volcanic rocks along the accreting plate margins, geologists have concluded that molten rock erupting on the surface probably originates in the mantle of the earth beneath the rigid lithopshere (see Figure 3). The mantle rocks, mostly silicates of iron and magnesium, extend from beneath the crust in the lithosphere to the outer core, twenty-nine hundred kilometers deep. These melts are believed to originate in the "primitive mantle," material that accumulated during the origin of the planet about 4.5 billion years ago and is just now becoming hot enough to be partially molten. This argument relies on the concept that the earth accreted from solar nebular material and was essentially cold until heated internally by the decay of radioactive potassium, thorium, and uranium. A strong argument for the model of a cold earth becoming hotter is that if the earth had been very hot or molten in its early history, it would not be possible for the partial melts we now find in oceanic ridge volcanoes to exist: they would have long since been erupted. For our purpose, however, we need only to understand that these volcanic melts, as they generate the new oceanic crust and mantle of the lithosphere, bring chemical elements from the interior into a surface or near-surface environment, usually submarine, where physical and chemical reactions result in accumulations of metal-bearing minerals of economic significance.

It is thought that the percolation of sea water into the erupted, cooling volcanic rocks is also an important mechanism for concentrating these minerals. This process of sea-water circulation in the hot rock, called hydrothermal circulation, is thought to cause solution and redeposition of the metal-bearing minerals, mostly sulfides. Some of the material so transported actually comes out on the sea floor along the Red Sea accreting plate margin; the sulfide muds along the axis of this sea are known to constitute one of the world's large ore reserves. In the Red Sea, these metal-rich sediments are the only ore bodies exposed, but we know from analogy with rocks exposed in other regions of the world, such as in Cyprus and western Newfoundland, that additional ore bodies may be forming in the newly generated oceanic lithosphere beneath the Red Sea brines.

On Cyprus, where some of the earliest known mining operations were undertaken, a complete cross section of oceanic crust and mantle and the associated ore deposits is exposed. Oceanic crust is composed of a thin coating of sediments over a layer of basalt, which comprises several kinds of minerals rich in iron and magnesium silicate. In addition to metal-rich sediments similar to those of the Red Sea, the Cyprus ore bodies contain large iron-copper-zinc sulfide deposits that occur within the basaltic rocks, both as isolated masses and as finely disseminated grains. The most common sulfide minerals are pyrite (iron), chalcopyrite (copper), sphalerite (zinc), and marcasite (iron). The copper-bearing sulfides covellite and

Figure 4. How continental "drift" changes the face of the earth. Continents, which ride on top as lighter portions of the lithosphere, move on geographic "tracks" determined by the simultaneous processes of accretion and subduction of lithosphere. Material from the earth's hot interior forms new surface at accreting plate margins, and oceanic lithosphere returns to the interior at consuming plate margins (see Figure 3). About two hundred million years ago the continents formed a single mass (at left), called Pangaea. The present-day configuration (at right) evolved through the subsequent opening and closing of oceans. The geographical distributions of oceans and continents in geologic history are reconstructed from measurements of the "magnetic anomaly stripes" (see Figure 2).

Figure 4

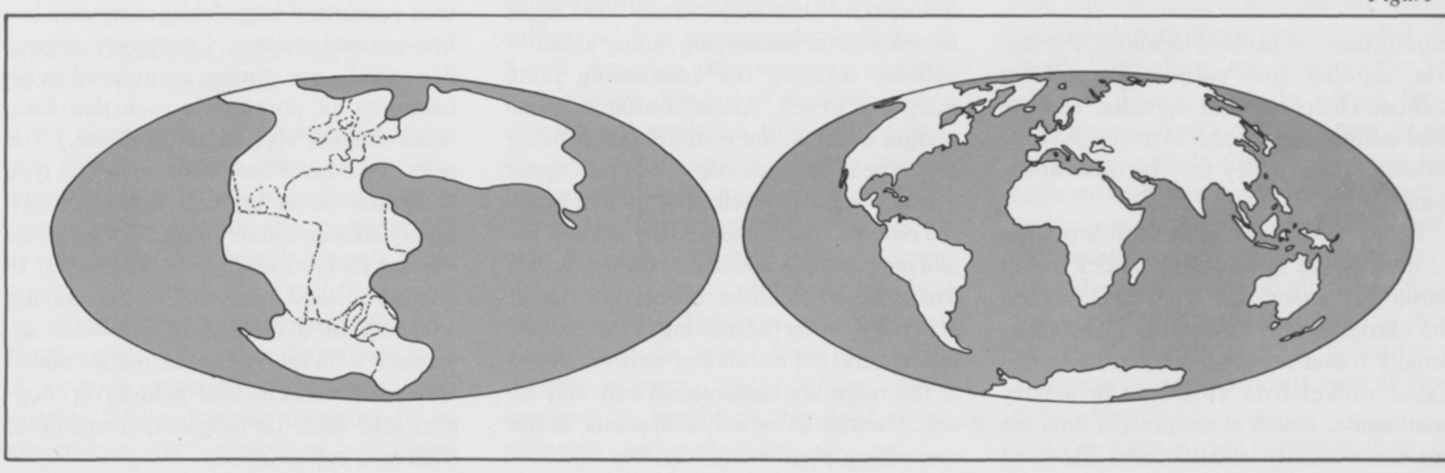


Figure 5

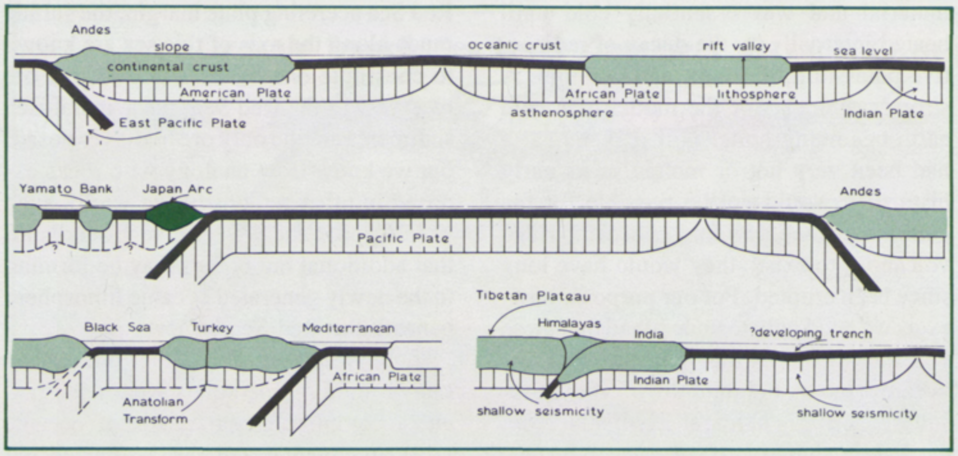


Figure 5. The tectonics of the earth's lithosphere. The drawing illustrates several lithosphere plates of the world, and their related continents, oceans, mountain belts, and island arcs. Depicted in the top sketch is the accreting plate margin beneath the Atlantic Ocean, which is still opening between the African and American plates. At the far side of the American plate, forces associated with the consuming plate margin at the interface of the continent and the Pacific Ocean build the Andean mountain system. The Pacific plate, shown in the middle sketch, is mostly rimmed by consuming plate margins, characterized by volcanic activity. Island arcs are chains of volcanic islands formed above the ocean-based consuming plate margins. The Himalayan mountain system (bottom sketch) was formed by continet-continent collision after plates moving together along a consuming margin closed the ancient ocean Tethys.

bornite occur in isolated localities. Pyrrhotite, another iron sulfide, the copper sulfides chalcocite and digenite, and the lead sulfide galena occur as trace minerals, although locally they may be more abundant.

Beneath the basalt, in the mantle portion of the oceanic lithosphere, is rock called peridotite. Associated with this layer are the chromium-bearing mineral chromite, usually found in isolated layers; disseminated nickel-iron sulfides, primarily pentlandite, which at the present time are not economically valuable; and dispersed gold and platinum-group metals, which may not be economically important as originally emplaced in the peridotite, but which may become concentrated by post-crystallization hydrothermal alterations.

HOW MINERALS CONCENTRATE AT CONSUMING MARGINS

As molten material comes up at oceanic ridges and crystallizes, the older crystallized crust and upper mantle move away from the ridge. This laterally moving lithosphere continues to cool and thicken, and eventually it becomes unstable: the lithospheric plate may "break" and begin to sink into the underlying, hotter asthenosphere, forming the consuming plate margin or trench. As the consuming plate margin evolves, the material that is being consumed, the oceanic crust and upper mantle, begins to melt. The molten material rises through the overlying lithosphere and may erupt as volcanics or may crystallize as large batholiths, or rock intrusions, at depth. During the melting of the oceanic lithosphere, the metals that were emplaced at the ridge are remobilized and may be concentrated as new ore deposits in the consuming plate margin system.

REMOBILIZED METALS IN ISLAND ARC SYSTEMS

In an entirely ocean-based consuming plate margin—an island arc system—the remobilized metals form sulfide ore bodies that are remarkably consistent in stratigraphy wherever found. Well defined successive zones in the deposits contain minerals bearing zinc, lead, copper, iron, silver, and gold. In addition to the massive sulfide deposits, minor porphyry copper deposits are found in some island arc systems, such as the Philippines. (Porphyritic rock consists of large feldspar crystals in a fine-grained matrix; "porphyry copper deposits" are those associated with batholiths of porphyritic rock that form when magma crystallizes at depth.) The principal copper ore minerals in this type of deposit occur in veins that also commonly contain minor amounts of minerals bearing molybdenum, gold, and silver. In addition, island arc systems often contain a variety of hydrothermal ore veins associated with the volcanics; metals mined from such veins include gold-silver, copper, lead-zinc, tin-tungsten, manganese, mercury, and antimony.

Figure 6

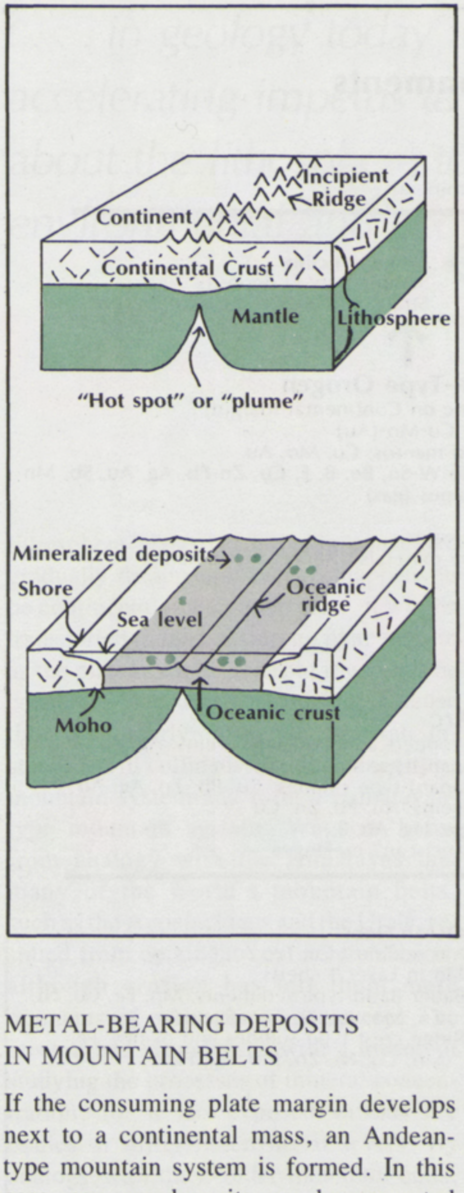


Figure 6. Ore deposition in oceanic regions. Environments for ore deposition are created by the rupture and separation of continents to form a new, opening ocean. The upper drawing depicts the incipient rifting, with "hot spots" or "plumes" of hot asthenospheric mantle penetrating the lithosphere as plate separation commences. Hydrothermal activity concentrates metallic elements that are then deposited on regions of the crust. As the ocean forms (see the lower drawing), the hydrothermal activity is enhanced by the presence of sea water. Deposits are formed locally in favorable places in the oceanic crust, and sometimes on the thin sediments that accumulate on the sea floor over the thermally active ridge region. The dots represent places where such deposits have formed. As the sea floor spreads, as a result of continuing accretion, the mineral deposits are carried along with the transported oceanic crust.

METAL-BEARING DEPOSITS IN MOUNTAIN BELTS

If the consuming plate margin develops next to a continental mass, an Andean-type mountain system is formed. In this case, new ore deposits may be generated by remobilization of metals not only in the oceanic lithosphere, but also in the overlying lithosphere and continental crust. Porphyry copper deposits are the primary kind of ore body associated with Andean-type systems. These deposits are generally of tremendous size, sometimes containing hundreds of millions of tons of ore, but they are very low-grade, from 0.5 to 1.0 percent copper. Even at such a low grade, however, the porphyry copper deposits supply a significant proportion of the world's copper. They also yield significant amounts of molybdenum, gold, and silver as byproducts.

Although the porphyry copper deposits are by far the most important ores associated with Andean-type margins, there are other deposits that are locally significant. Some of the porphyry-type deposits of the western United States contain economically significant amounts of lead-zinc sulfides such as galena and sphalerite. In South America the porphyry copper-molybdenum deposits of the Andes show an eastward gradation to porphyry lead-zinc-silver deposits and, in some cases, a further gradation to tin-rich deposits. There are also economically important vein deposits associated with the intrusions and volcanics of the Andean-type mountain belts. The more important metals that may be mined from these veins include copper, molybdenum, gold, tungsten, tin, beryllium, zinc, lead, silver, antimony, and manganese.

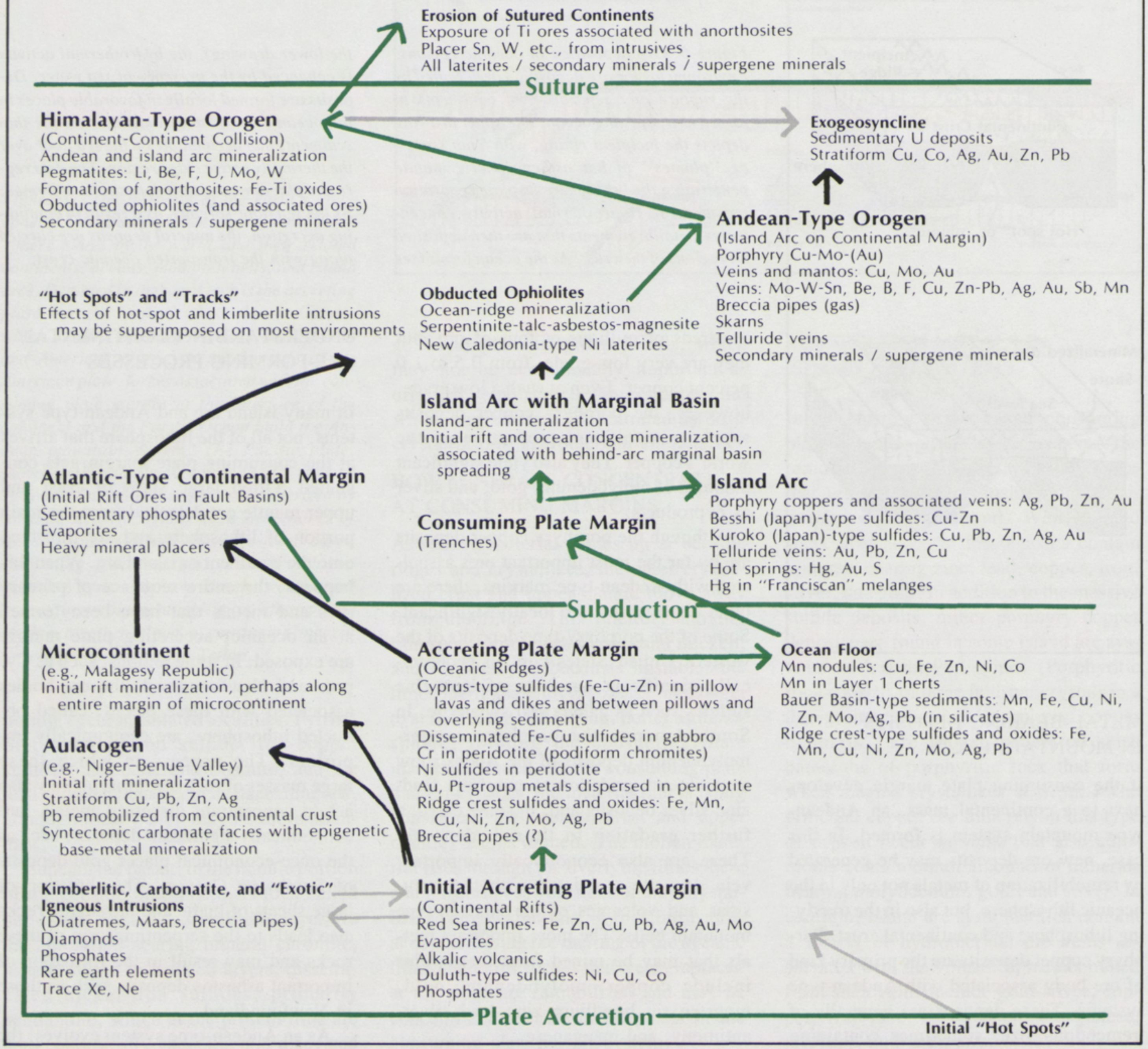
UNDERSTANDING CONTINENTAL ORE-FORMING PROCESSES

In many island arc and Andean-type systems, not all of the lithosphere that arrives at the consuming plate margin gets consumed. Often large slabs of crust and upper mantle get detached from the main portion of lithosphere and are thrust up onto the continent or island arc. When this happens, the entire sequence of primary ores and metals that have been formed at an oceanic, accereting plate margin are exposed. In some regions, such as Cyprus and Newfoundland, the ore bodies associated with these pieces, called obducted lithosphere, are economically important. The process in which these large masses of rock are thrust up may also act to concentrate dispersed metals into economically significant deposits, such as the once-economical placer gold deposits of Southwest Oregon. The thrusting of large sheets of mafic and ultramafic rocks also leads to the serpentinization of these rocks and may result in the formation of important asbestos deposits such as those in Newfoundland.

As an Andean-type system evolves, the

Figure 7

Lithosphere Plate Cycle and Ore Environments



". . . in geology today there is an accelerating impetus to apply recent discoveries about the lithosphere to practical environmental and economic problems"

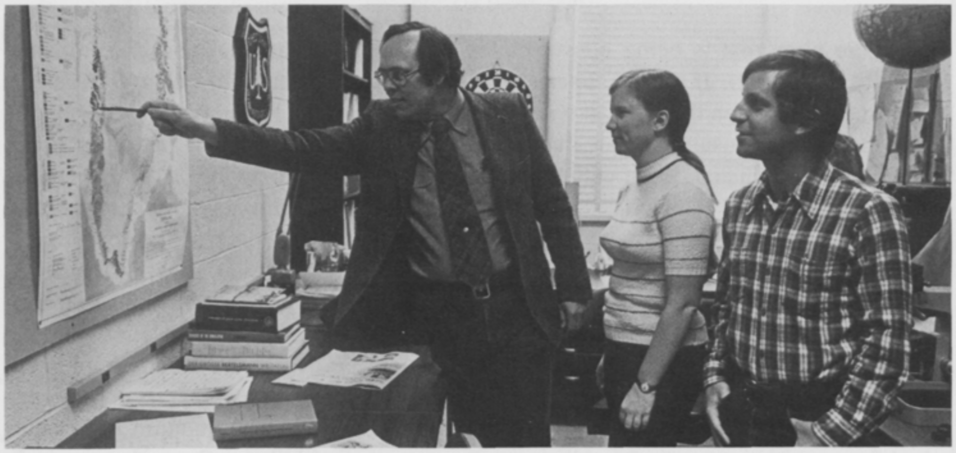
lithosphere plate that is being consumed gradually disappears. If there happens to be continental mass on the plate, it will be transported to the consuming plate margin as the plate is subducted, but it will not be consumed because it is much less dense than the underlying mantle material. Instead, it will collide with the Andean-type mountain system and form a Himalayan-type mountain system. We now know from analogy with the Himalayas that many of the world's mountain belts, such as the Appalachians and the Urals, resulted from continent-continent collision, although erosion has left them mere remnants of what they once were. The erosion has provided us with a means of studying the processes of mineral concentration, for it has exposed various ore bodies at different erosional levels. By analogy with these older mountain belts, we can identify the ore deposits that may be forming under the Himalayas and Tibetan Plateau at the present time.

The average thickness of most continental crust is thirty-five kilometers, but in the Himalayas it is approximately seventy kilometers. We can, therefore, estimate the degree of erosion of older mountains by comparing the thickness of continental crust there with the seventy-kilometer thickness of the Himalayas. The Grenville Province of eastern Canada, for example, is now assumed to be a deeply eroded remnant of a Himalayan-type mountain belt: the underlying crust is about thirty-five kilometers thick, indicating that about thirty-five kilometers of crust have been eroded away. Exposed in a belt within the Grenville Province are a number of small batholiths, or plutons, that have economically important iron-titanium ore bodies associated with them. By analogy, minerals bearing these metals are presumed to be forming at the present time at depths of thirty-five kilometers or less under the Tibetan Plateau of the Himalayan system.

LOOKING TO THE FUTURE OF ECONOMIC GEOLOGY

In this brief and schematic discussion, I have considered only the scientific—perhaps still impractical—aspects of our present understanding of the genesis of ore deposits. The economics of resource exploitation, involving political, financial, and environmental factors, is a fascinating and exceedingly complex subject, more or less separate from the scientific background. Yet in geology today there is an accelerating impetus to apply recent discoveries about the lithosphere to practical environmental and economic problems, and the plate tectonic models for the genesis of mineral deposits provide a framework for new approaches. Cornell graduate students who are working in this area receive instruction in engineering, materials science, and economics, as well as in the conventional and more speculative aspects of theoretical geology and geophysics, and they are being prepared for positions of leadership in the future of economic geology.

The development of mineral resources has high priority in the world today, for it appears certain that a "metals crunch" similar to the current "energy crisis" is in our future. We need not, however, take the pessimistic view implied by the "gold is where you find it" philosophy. Rather, we can look to significant developments—in mining techniques and in the application of scientific theories of ore genesis and distribution—that will bring mineral recovery technology to a new age.



Professor Bird and two graduate students, William Rathke and Maura Weathers, are developing a model of ore genesis based on plate tectonics and geologic observations.

John M. Bird, a geologist with special interest in applying plate tectonics to the interpretation of geologic history, is now in his fifth year as a Cornell professor of geological sciences. His first article for this magazine, in 1973, was a general discussion of the plate tectonic concept.

Bird is recognized as an authority on the evolution of mountain belts. His research in this area has involved extensive field work in the mountain ranges of Europe and North America; some of this was conducted in 1968 when he went to Poland as an exchange visiting scientist under the auspices of the National Academy of Sciences. His activities in this field of geology include participation in studies sponsored by the United States Program for the International Geodynamics Project.

His current work also includes study of ocean margins as potential sources of minerals. He is a member of the JOIDES (Joint Oceanographic Institutions' Deep Earth Sampling) committee responsible for planning the deep drilling of ocean margins. At Cornell, he and David L. Kohlstedt of the Department of Materials Science and Engineering are involved in extensive studies of rare metallic minerals and their implications for the origin of the earth's mantle.

Bird joined the Cornell faculty after eleven years at the State University of New York at Albany, where he served as chairman of the Department of Geological Sciences. Previously he had been a senior research associate at the Lamont-Doherty Geological Laboratory of Columbia University. He is a graduate of Union College and holds M.S. and Ph.D. degrees in geology from Rensselaer Polytechnic Institute.

He is currently chairman of the northeastern section of the Geological Society of America, a fellow of the Geological Society of America and of the Geological Association of Canada, and a member of the American Geophysical Union, the American Association for the Advancement of Science, and Sigma Xi.

CLUES FROM MARINE GEOLOGY IN THE SEARCH FOR OIL AND MINERALS

by Daniel E. Karig

The hope that mineral resources from the sea would offset impending shortages in continental supplies has been somewhat slow in materializing. In part the problem is economic, one of high recovery costs, but to a considerable extent it stems from a lack of knowledge of the resource-producing processes in the marine environment. The value of such knowledge is becoming recognized in efforts to locate not only minerals but also oceanic petroleum deposits.

As a result, academic and economic interests have recently begun to interact in studies of marine geologic processes. At an increasing rate, research funding is becoming more resource- and product-oriented and mining and petroleum companies are becoming more receptive to the ideas and implications of the relatively recent, fundamental concept of plate tectonics. The search for marine resources has also had the effect of broadening the scope of research, and larger, multidisciplinary projects are becoming common.

These various trends are reflected at Cornell in current research of the Department of Geological Sciences, which includes an integrated study of the nature and behavior of consuming plate margins. These plate margins have come under special scrutiny because they appear to be sites where important ore-forming processes occur and might be observed, and also where exploitable mineral and hydrocarbon resources might be found.

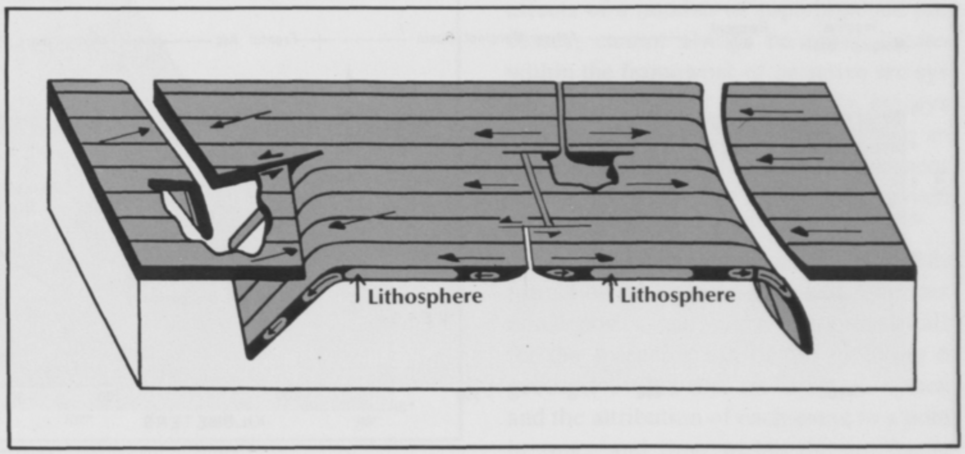


Figure 1. Block diagram showing several types of lithosphere plate boundaries. Converging arrows mark converging plate boundaries, where oceanic plates sink down into the deeper parts of the earth. New crust and lithosphere is formed at accreting margins, shown by diverging arrows.

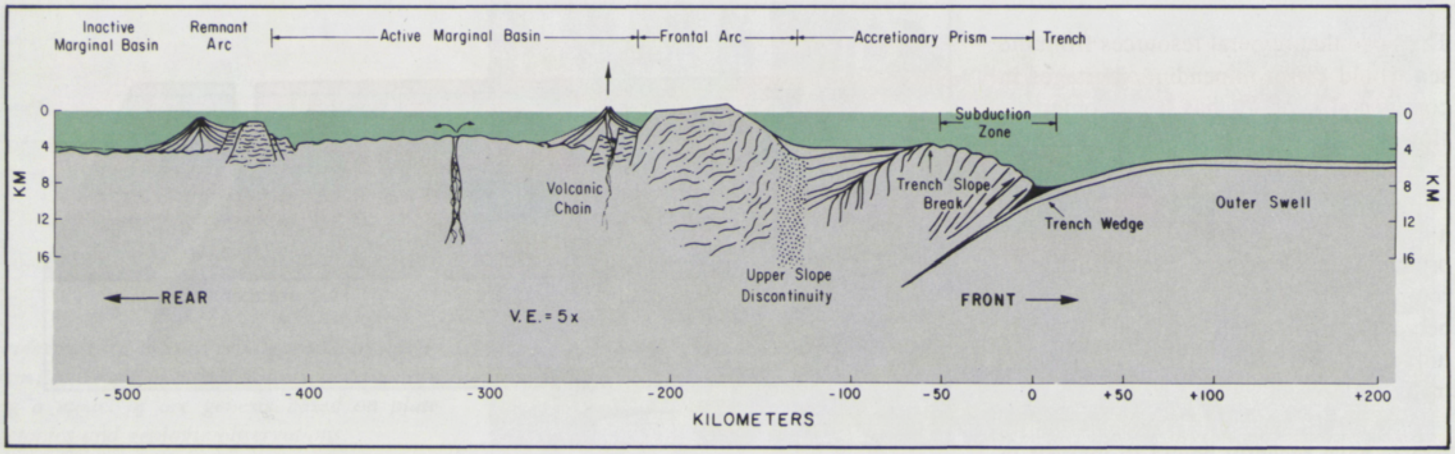
Although this figure is schematic, it closely resembles the plate pattern seen across the southern Pacific Ocean: Australia would be on the left and Peru on the right.

(This figure is taken from published work of Bryan L. Isacks and Jack E. Oliver of Cornell's Department of Geological Sciences, and their associates.)

IMPLICATIONS OF EVENTS AT CONVERGING PLATE MARGINS

Consuming plate margins are a common type of boundary between the large rigid plates or spherical caps that constitute the outer one hundred or so kilometers of the

Figure 2. A generalized cross section through an island arc system. Next to the trench *is a zone of deformation and accretion (the* accretionary prism*) where material is scraped off the downgoing plate and added to the arc. The island of Nias, where a Cornell group is making studies, exposes a part of this zone: the feature labeled* trench slope break. *Behind the accretionary prism is a zone (labeled* frontal arc*) where strong uplift and volcanism are observed. It is in this zone that the islands of an arc system, such as Tonga or the Aleutians, generally occur. Behind the frontal arc there is often a zone of extension where new sea floor and small ocean basins are created.*



earth. (In addition to the consuming margins where plates converge, there are extensional margins where new ocean crust is formed, and transform margins where plates slide past each other.) Most of the converging boundaries are arcuate in map view, which has led geologists to call them arc systems. Such systems nearly encircle the Pacific and also form a belt from the Alps through the Himalayas to Indonesia.

Of all the varieties of plate margins, the consuming type is the most complex and least understood, but the general behavior along these boundaries has been established: one plate carrying oceanic crust is pushed or slid beneath the other plate, and this process results in a typical and defining set of gross characteristics. One of the most prominent of these is a trench along the boundary, caused by elastic depression of the downgoing oceanic plate by forces beneath the upper plate; often these trenches reach depths of nine or ten kilometers, nearly twice that of the normal ocean basin. Another characteristic is a spectacular chain of volcanic cones lying one hundred to three hundred kilometers behind the trench on the upper plate.

Energy is dispersed at the plate boundary both by earthquakes and by several heat-transporting processes, one of which is responsible for the volcanic activity. The earthquakes are unique in that they occur along a dipping surface to depths up to seven hundred kilometers and mark the path of the plate as it becomes reabsorbed into the earth's mantle.

Although the strong similarities in gross character of arc systems implies that a single fundamental process controls plate convergence, there are wide variations in detail that suggest the influence of other

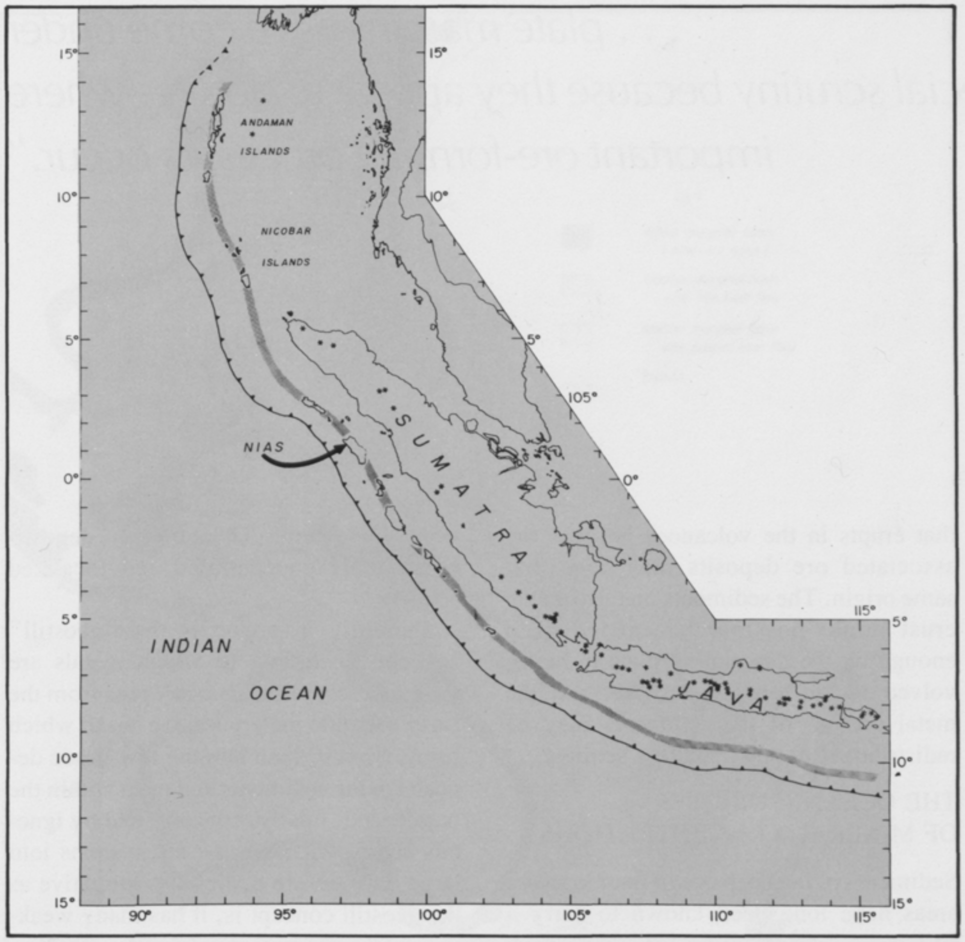


Figure 3. The area near Nias, the Indonesian island that Cornell geologists have been mapping. Nias is the largest and only easily reached island in the chain lying west of Sumatra. This chain is almost the only area in the world where structures within an active arc system can be clearly seen.

processes. One of our major goals at Cornell has been the description and understanding of these variations in an attempt to discover the responsible processes. Early in this apparently academic exercise, we realized that these same variations are of great interest to those searching for exploitable resources.

CLUES IN FINDING MINERAL AND HYDROCARBON DEPOSITS

The problem of relating arc processes to resources is not simple. Most metallic ore deposits are found in mountain belts, in highly deformed rocks or associated with bodies of igneous rocks that mark the roots of old volcanic centers. It is often clear that the deformation and igneous activity actually occurred along active arc systems and that later these rocks were uplifted and deeply eroded. But how is one to know what specific process led to the concentration of metals? In active arcs, only the morphology and shallow structure can be readily observed, and in mountain belts both of these are destroyed by erosion or later deformation. The original position of the deeper rocks, which have suffered the effects of a number of superimposed processes, cannot always be easily located within the framework of an active arc system. Hydrocarbon resources in arc systems pose a different problem. There are large basins formed in this environment, but these seem to defy the rules that govern the evolution of ordinary basins.

In trying to gain an understanding of the formation of both mineral and hydrocarbon deposits, one attractive approach calls for the spreading out of the spectrum of geologic events that mold an arc system and the attribution of each event to a point in space and time within the arc framework. We have tried to use this approach by mapping the geology of islands within the active arc system. The position of these islands in the arc framework is clearly defined and erosion has cut deep enough to reveal a part of the internal structure of the arc. Unfortunately, there are very few such islands and they invariably lie well off the beaten track.

FIELD STUDIES ON ARC ISLANDS IN INDONESIA

Possibly the best examples of islands in which there is exposure of the scraped-off

" . . . plate margins have come under special scrutiny because they appear to be sites where important ore-forming processes occur."

and deformed ocean floor sediments that have built the seaward edge of the arc occur in the chain of islands one hundred to two hundred kilometers west of Sumatra. Some of these are nearly uninhabited, cannot be reached without a chartered vessel, and are nearly impossible to move about on. We have been studying structures on the island of Nias, the largest and most densely populated of the chain. Even though a boat regularly visits Nias, work on the island is slow and difficult. Nevertheless, the scientific rewards have more than justified the discomfort. Outcrops along the jungle streams have shown us what structures are developed in the sediments that are scraped off the downgoing oceanic plate. Already these results have clarified our interpretation of similar structures in an old belt of arc rocks in California.

Work on Nias is also helping us to determine the role of these scraped-off oceanic sediments in the generation of arc-related metal deposits. There may be a relationship, strange though it might appear, between these sediments and the arc volcanoes. There is a great deal of interest in determining the origin of the material that erupts in the volcanoes because the associated ore deposits may have that same origin. The sediments on the oceanic crust might possibly be carried deep enough on the downgoing plate to be involved in the igneous activity, and the metal content of the sediments may be redistributed in new, shallow settings.

THE OCEANIC ORIGINS OF MINERAL CONCENTRATIONS

Sediments of the deep ocean floor in many areas have long been known to carry a surface concentration of ferromanganese nodules that also are rich in cobalt, nickel, and other metals. More recently, coring and deep-sea drilling have shown that iron, zinc, copper, and manganese are concentrated in the lowermost sediments, immediately above the basaltic ocean crust. It was first wondered if these metals originated in primitive juices from deep in the earth, but now it is recognized that they result from hydrothermal flow through the young and still very hot basaltic lavas that form the ocean crust. Hot water leaches the metals present in low concentration in the lava and carries them up into the thin overlying sediments near areas where new ocean floor forms. There they are deposited in more concentrated and localized form.

Currently in vogue is the "geostill" concept, according to which metals are progressively refined as they pass from the earth's mantle material to the basalt which forms from it, then into the low-grade deposits in the sediments and even within the basalt, and, finally, concentrated by igneous activity beneath the arc systems into large but rare ore bodies. As attractive as the geostill concept is, it has many weaknesses. One question related to our Nias work is whether the sediments with their metals could actually be carried far down beneath the arc or whether they are all scraped off near the trench.

Another way in which ores from the ocean floor can be incorporated into mountain belts is by the transportation of entire sheets of the ocean floor, basaltic crust as well as sediments, up onto continental crust. Such sheets, termed ophiolites, not only carry small copper and zinc deposits on their tops, but also contain nickel and chromium deposits in the deeper crustal or upper mantle sections. The extensive nickel ores of New Caledonia and the large

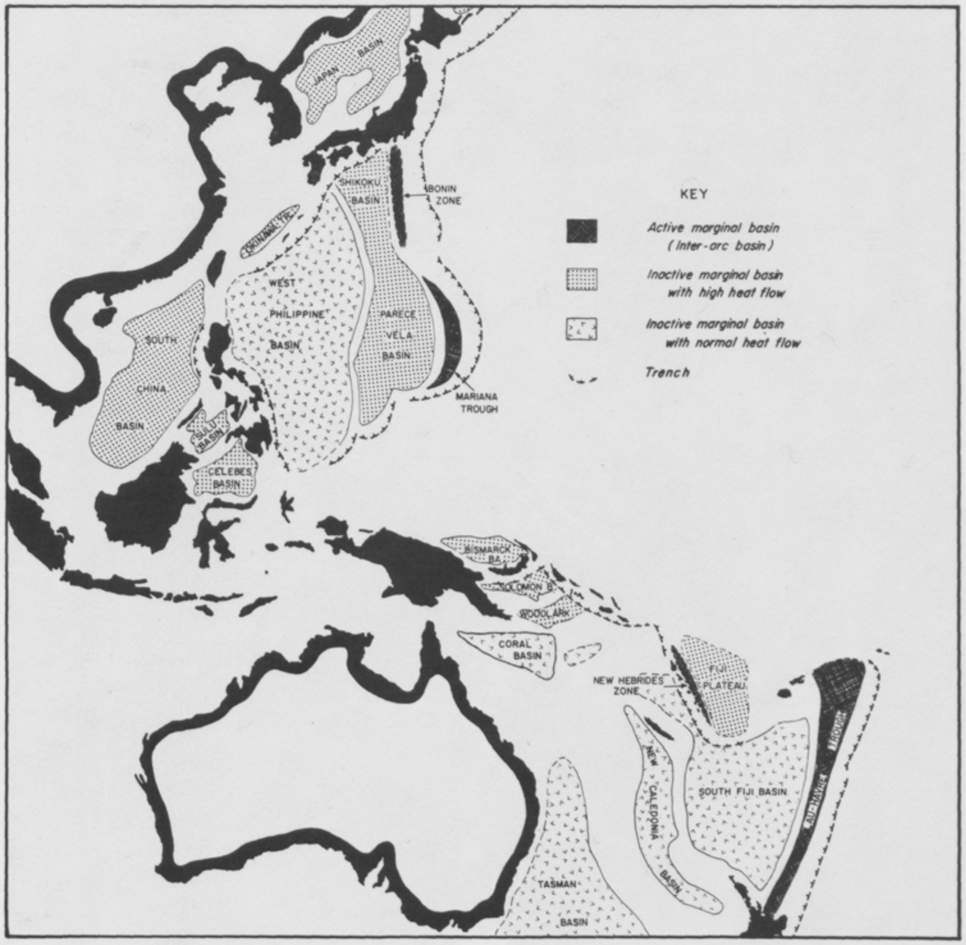


Figure 4. Map of the Western Pacific-Indonesian region, showing most of the world's marginal basins. In these strange small oceans, a large percentage of the sediments from continental erosion is trapped, and the conditions are very promising for the accumulation of petroleum oil and gas.

refractory chrome deposits in the Zambales Ranges of the Philippines are now recognized as being parts of such ophiolites. Despite the economic interest in ophiolites, we still have not conclusively determined how they come to be emplaced.

CORNELL STUDIES OF MARINE GEOLOGIC PROCESSES

It falls to the academic marine geologists to elucidate the behavior of recent arc systems and to search for the mechanism that might cause ophiolites to be emplaced. We at Cornell have been approaching the problem by collecting a large number of geologic and geophysical profiles across active arcs and by coupling the variations in arc characteristics with changes in properties such as rate of plate convergence and the type of sediment cover on the downgoing plate. This study is only in its initial phase, but we have already begun to narrow down the possible transport mechanisms of ophiolites, as well as to suggest a correlation between the internal structure and the external morphology of active arcs.

Another project in which we have been involved for several years is an effort to explain the formation of the small ocean basins, or marginal basins, that lie behind the island arcs. Although scientists originally expected that the region around converging plate margins should be one of compression, our oceanographic observations suggested that young sea floor underlay the marginal basins. This seemed strange because young ocean crust is related to extensional or separating plate margins. In some basins we even identified the zones where the new crust was forming, and could demonstrate that sea-floor spreading was taking place. These observations are now accepted, but there is still much debate over the interpretation of the spreading and how it is related to converging plate margins.

1. Geologic mapping on a tropical Indonesian island is best done by working along streams, which provide the easiest access to remote areas and also the most favorable locations for observations. Away from the streams, the original rocks have been covered or seriously modified by vegetation and weathering. Professor Karig appears in this photograph, taken on Nias.

2. Karig and a guide used a dug-out canoe to search for outcrops in a mangrove swamp on Sumatra.

3. At times the Cornell geologists working on Nias would come across ancient stone statues in the forest, marking the sites of long-forgotten villages.

4. The charm of rural scenes in western Sumatra more than offsets the difficulties encountered in doing geologic study in this exotic area, according to Karig.

5. The ancient culture of Nias is still largely preserved in some villages. A typical feature is the jumping stone (foreground) used for ritual high jumping, which is performed without benefit of a movable bar or sawdust pit. While on Nias, the Cornell geologists often stayed in villages like this and ate the local food, mostly rice, tubers, and vegetables. Their base of operations was the island's main hotel, which, although it has no running water, does provide lighting for after-dark work.

1

2

4

3

5

"... these marginal basins have become important targets in the search for untapped hydrocarbon resources."

OIL IN OCEANIC BASINS, ORE IN CONTINENTAL BELTS

Adding to the interest of our study is the fact that these marginal basins have become important targets in the search for untapped hydrocarbon resources. The process of petroleum synthesis in these basins, which rim Asia from the Sea of Okhotsk to the Andaman Sea, begins with the trapping of the immense sediment load issuing from the Asian rivers. The rapid deposition of these sediments, coupled with high sediment temperatures caused by the still hot and young ocean crust beneath, results in a very rapid maturation of organic material into hydrocarbons. In fact, this process has proceeded so rapidly that unexpected and dangerous gas pockets were encountered in the early drilling of some basins and a number of blowouts occurred. An understanding of this environment was also hampered by the belief that the basins were underlain by rocks of the same type and age as those mapped on the surrounding land areas. An extensional origin, as indicated by our studies, would result in much younger basins which would have not only a different evolution, but also very different characteristics.

Interest and discoveries in the marginal basins are rapidly increasing. This is the reason that several Asian countries have placed so much emphasis on their territorial claims to tiny uninhabited coral islets in the China seas. It is also one reason for the seeming conversion of Singapore to an oil boom town, serving as the center for many facets of the petroleum search.

A more exotic aspect of our marginal basin studies has been the suggestion that an analog of the mechanism deduced for basin formation may be the cause of many continental ore deposits. Along several arc systems that border continents, we find an extensional zone, or rift, with precisely the same relationship to the arc that the marginal basins bear. These rifts may eventually open far enough to become basins, but in their early phases they are associated with the eruption of very silica-rich, fluid lavas from calderas. Calderas are large, complex volcanic centers with collapsed centers, one example of which can be seen at Crater Lake; eroded calderas are the sites of many mining camps in the Colorado Rockies and elsewhere. The suggestion is that the occurrence or absence of extension within arcs may be one of the processes that differentiate barren from ore-producing mountain belts.

PROJECTED LARGE-SCALE STUDIES OF ARC SYSTEMS

Now in the planning stage are a number of more complex and sophisticated studies of arc systems. Most of these are not only multidisciplinary but also international in scope. One is IPOD (International Program of Ocean Drilling), to which a number of nations, including Japan, Germany, and the Soviet Union are contributing scientific and monetary support. IPOD is a continuation of the Deep Sea Drilling Program, but with more advanced technological capabilities and more ambitious goals. More than a dozen drill holes penetrating up to several kilometers into the crust of island arcs are planned to test directly the internal structure and composition of the arcs. Extensive survey programs that will precede and guide the drilling are themselves major pieces of scientific research. Although scientifically oriented, the IPOD program will draw heavily on oil exploration technology and personnel and cannot help but be profitable to both scientists and those with economic interests.

Another major arc program, and one in

Karig (left) and graduate student Greg Moore study seismic reflection profiles of the oceanic trench slope off Nias just before leaving for their recent two-month field trip. Almost at the end of their stay, Moore slipped while crossing a stream, broke an ankle, and had to be carried out–over six kilometers of rough, muddy, and densely vegetated terrain–on a makeshift palanquin. Last year, on his first trip to the island, he contracted malaria. Both men lost weight during the rigorous expedition. However, the "scientifically rewarding" results more than compensate for the difficulties, they claim.

which Cornell is strongly involved, is the Southeast Asian IDOE (International Decade of Ocean Exploration) Program. This program attempts to use both oceanographic and land geological techniques to study metallogenesis and basin formation in the arc systems of southeast Asia. This area is particularly suited to such a study because it contains such a wide variety of arc types. In this project, United States scientists will be working jointly with geologists from Indonesia, Malaysia, Thailand, and the Philippines in studies that will not only generate scientific data but will also constitute a program of training, education, and mutual assistance.

Daniel E. Karig submitted this article the day before he left for two months of field work in Indonesia. He returned in March with new data for his study of island arc formation and evolution. A marine structural geologist, he is combining techniques and approaches of marine geology, geophysics, and geotectonics in developing an understanding of geological processes in the ocean environment.

In addition to studying the Indonesian arc system, he is involved in marine geological investigation of the Middle American Trench off the coast of southern Mexico. His professional activities include membership on the planning committee for the International Program of Ocean Drilling and in the Inter-Union Commission on Geodynamics.

Karig took his undergraduate work in geology at the Colorado School of Mines, and after working as a civil engineer for the Los Angeles flood control district and serving in the United States Army Corps of Engineers, he returned to Colorado for a master's degree in geology. While at the Colorado School of Mines, he was the recipient of the W. A. Tarr Award of Sigma Gamma Epsilon, and was awarded a Hays-Fulbright grant for a year of research in New Zealand. He then studied at the Scripps Institution of Oceanography, University of California at San Diego, for a Ph.D. degree in earth science, awarded in 1970. After spending a year at the Scripps Institution as a research geologist, he became an assistant professor of geology at the University of California at Santa Barbara.

Karig joined the Cornell faculty in 1973 and was promoted to associate professor in 1975.

He is a member of the Geological Society of America, the American Geophysical Union, and the Geological Society of Malaysia.

HOT SPRINGS, GEYSERS, AND GEOTHERMAL ENERGY

by Donald L. Turcotte

Everyone knows that hot springs occur. Yellowstone National Park and other areas are famous for the geysering that is produced by a combination of boiling water and dissolved gases. But although hot springs and geysers are familiar natural phenomena, very little is known about their origin. Geochemical studies have shown that the water involved is circulating ground water. But what are the sources of heat?

Before the energy crisis, this question was primarily of academic interest. Today it is a major focus of the government's energy research program. The reason is geothermal energy.

The only producing geothermal field in the United States today is The Geysers, an area north of San Francisco. Here dry steam at an average temperature of 250°C is tapped from wells about fifteen hundred feet deep, and used directly to run turbines. This is a viable commercial operation with an installed capacity of six hundred megawatts, equivalent to half the power used by the city of San Francisco. But what is the potential for other fields? What are the criteria for finding them? And how can the heat be extracted?

EXTRACTING HEAT FROM THE EARTH'S INTERIOR

All geothermal energy is derived from the earth's hot interior where heat is produced by the decay of radioactive elements (^{235}U, ^{238}U, ^{232}Th, and ^{40}K). There are basically two sources of the heat for geothermal energy: the natural geothermal gradient, and cooling bodies of magma (liquid rock). The main types of systems that might be tapped for energy are hot dry rocks, hydrothermal systems producing hot water or steam or both, and geopressured systems producing hot water (and natural gas).

Processes suggested to extract heat from hot rocks are based on the idea of circulating water at depths where it would heat sufficiently to be usable for the production of electricity. Heat conduction causes a near-surface temperature gradient of about 20°C per kilometer, and assuming that an economically competitive geothermal energy plant would require a hot-rock temperature of 200°C, sufficient heat could be reached at a depth of about ten kilometers. In fact, in areas of relatively high heat flow, it is possible to drill into rock at this temperature at much shallower depths. Extraction of the heat is a more difficult matter, however. The Energy Research and Development Agency (ERDA) has proposed to circulate water between two wells in order to extract heat. But the problems associated with injecting and withdrawing the water while circulating it through fresh hot rock are severe, if not insurmountable.

An alternative way of extracting geothermal energy is by tapping natural reservoirs of hot water. These may reach the surface through convection as hot springs or geysers, or they may lie underground where they must be located and reached by drilling.

HOT SPRINGS AND THEIR SOURCES OF ENERGY

The hot springs of the eastern United States are generally attributed to the deep circulation of ground water in a near-normal geothermal gradient. The principal eastern hot springs are near the Virginia-West Virginia border and in Georgia. At Hot Springs, Virginia, the water reaches a temperature of 106°F, and at Warm Springs, Georgia, it reaches 87°F. In these

Figure 1

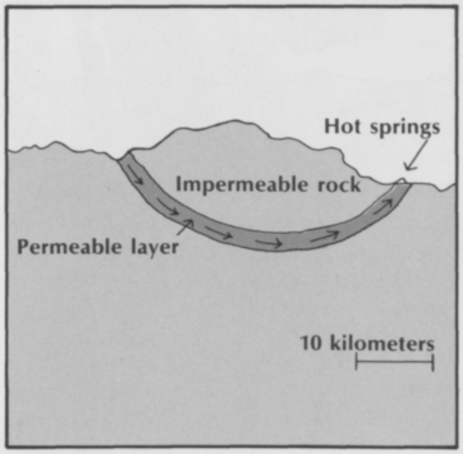


Figure 2

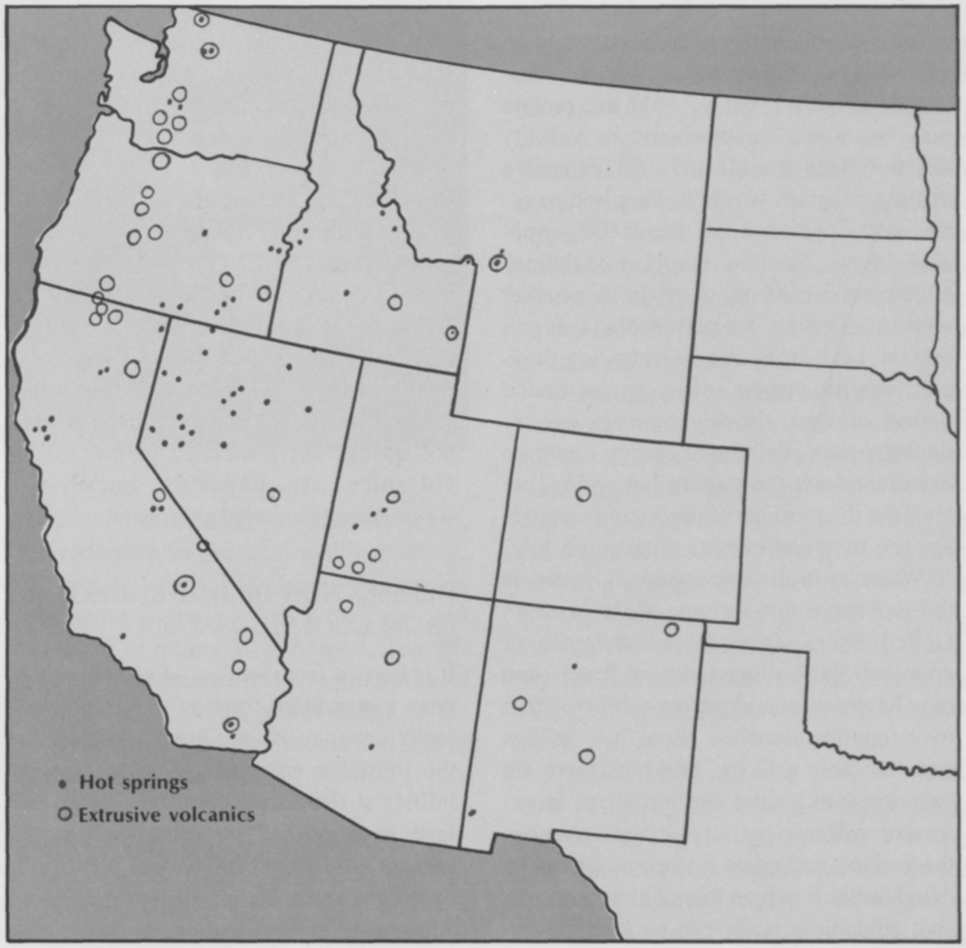


Figure 1. The deep circulation of ground water believed to occur near hot springs in the eastern United States. These springs are generally not hot enough to be used for the production of electricity.

Figure 2. The association of recent volcanic activity and hot springs in the western United States. The dots indicate the locations of hot springs with geothermal power potential; the circles represent extrusive volcanics with an age of less than ten thousand years. Although many of the hot springs appear to be related to recent extrusive volcanism, some must be generated by other thermal sources such as intrusive volcanic activity.

"But what are the sources of heat? Today (this question) is a major focus of the government's research program. The reason is geothermal energy."

cases, water is believed to circulate in an arched layer of permeable rock, as illustrated in Figure 1; but although this picture may be correct qualitatively, its validity has not been established. An extensive drilling program would be required to establish the presence and role of the permeable layer. And no model calculations have been carried out to establish whether water convecting in a permeable layer *can* extract heat from the surrounding low-permeability rocks over an extended period of time. In any case, it is very doubtful that geothermal energy could be extracted from the eastern hot springs, at least for the purpose of producing electricity; the temperatures are simply too low.

Water at high temperature is found in the extensive hot springs of the western United States, many of which reach or approach the boiling point of water, and may have associated geyser activity. Most investigators associate these hot springs with volcanic activity, of which there are two types, extrusive and intrusive. In extrusive volcanic activity, magma reaches the surface; and since surface rocks can be dated, areas in which there has been extrusive volcanic activity can be identified.

The areas of the United States where there has been volcanic activity in the last ten thousand years are shown in Figure 2. It is estimated that at depth, volcanic rocks of this age may still be cooling. Also shown in Figure 2 are the locations of hot springs with water temperatures, at depth, greater than 150°C. (The water temperature at depth can be deduced from the chemistry of the surface water.) It is clear from the locations of these two kinds of features that recent volcanism does generate hot springs, but that there are also many hot springs not associated with extrusive volcanics. An important question is whether these are also associated with volcanism.

GENERATION OF HOT SPRINGS FROM COOLING MAGMA

It is known from studies of eroded mountains that a large fraction of the volcanic rocks never reach the surface. These are the intrusive volcanics. The magma solidifies at depth and there may be no surface evidence of its presence. At the present time there is no way of identifying cooling magma bodies at depth, although attempts to locate them by seismic studies

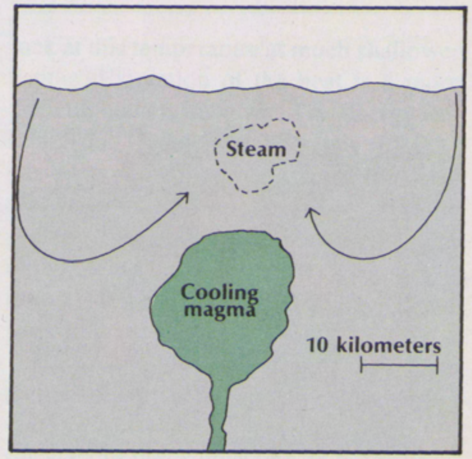
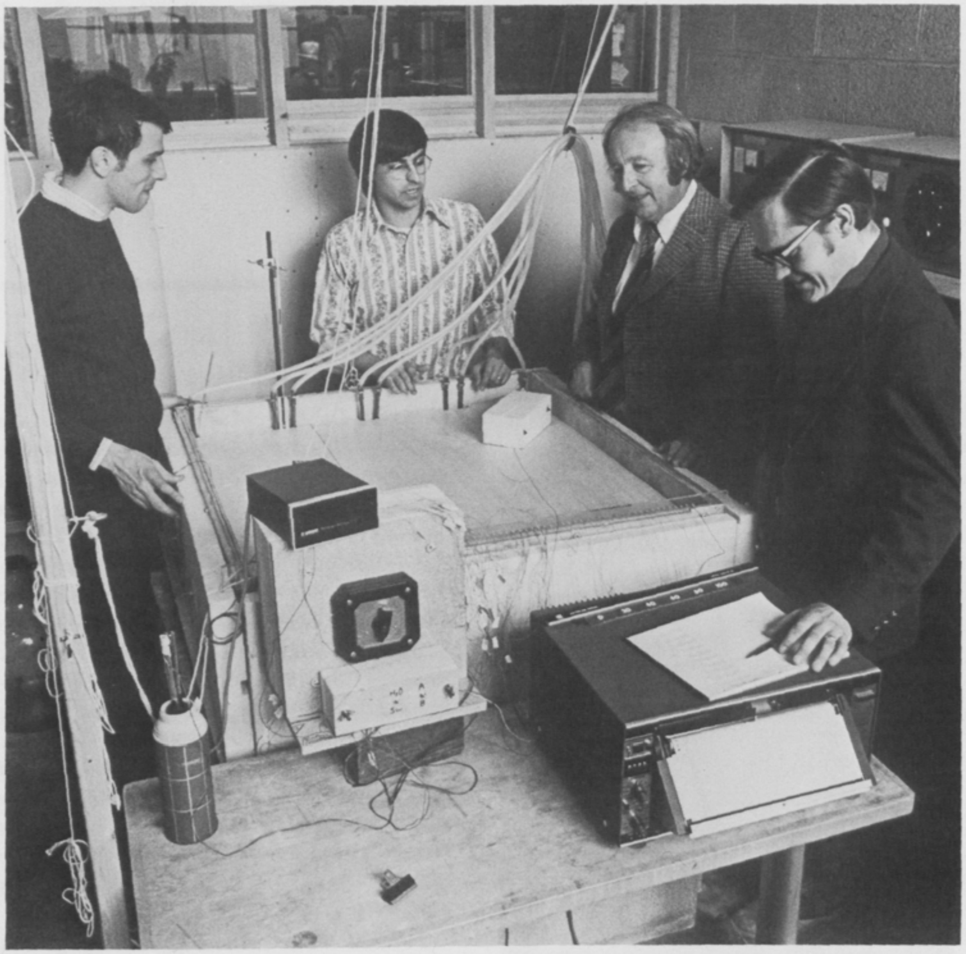


Figure 3. The mechanism thought to account for the generation of hot springs by cooling magma. Ground water circulating near the hot magma chamber is heated by conduction and then rises because of its decreased density.

are being pursued actively. (The seismic reflection profiling techniques discussed by Sidney Kaufman elsewhere in this issue are potentially applicable to this kind of search.) It is probably reasonable to assume that the large, high-temperature hot-spring and geyser areas are associated



The Cornell research group studying two-phase convection in a porous medium includes (left to right) graduate students Bob Ribondo and Carl Sondergeld and professors Donald L. Turcotte and Kenneth E. Torrance. The "sand box," filled with glass beads and water, is used to simulate geothermal reservoir circulations; in this experiment, grids of thermocouples are being used to study temperature distributions. Near Torrance is a 24-channel multipoint recorder, and at the left is a thermally insulated switch that feeds data from 48 thermocouples into a digital panel meter.

with cooling magma at depth, but whether all hot springs of the West are associated with magma bodies is simply not known.

A cooling magma chamber is thought to generate hot springs through thermal convection in a mechanism illustrated in Figure 3. Cold ground water flows downward, probably through cracks and faults. As the water approaches the magma chamber, it is heated by conduction. As the temperature of the water increases, its density decreases; it becomes buoyant and rises to the surface, through cracks and faults, as hot springs. As the water rises, its pressure drops, and if the water is sufficiently hot, the reduction in pressure may cause it to convert or "flash" to steam. The reason that steam is produced in some cases and hot water in others is not known. The difference may be due to the availability of ground water, or the permeability of the rock (dependent on the number and size of cracks), or both.

CIRCULATION SYSTEMS: AN AREA FOR RESEARCH

Relatively little data are available on the behavior of the circulation systems at depth. Information on The Geysers area in the western United States is unavailable because it is proprietary. The most extensive studies have been carried out on the Wairakei area in New Zealand. We do know that when steam in the ground is tapped by a well, its behavior appears to be similar to that of a supply of natural gas at a wellhead: the steam does not appear to be replenished by natural processes during a withdrawal time of ten to twenty years.

Very little research has been carried out on the circulation systems associated with hot-water, two-phase, or dry-steam geothermal systems. It is possible that by drilling into a hot-water system and removing the water sufficiently rapidly, the system could be changed into a two-phase or a dry-steam system. It might also be possible to affect a hot-water system by reducing the availability of ground water, by changing drainage patterns, or in other ways.

Unfortunately, drilling is very expensive. Virtually all drilling today is being carried out by oil companies that are searching for dry-steam systems in the same way they would search for oil or gas fields. A research drilling program is being carried out on a modest scale in geothermal areas by the United States Geological Survey, but so far it has produced relatively little information of value.

THE CORNELL PROJECT ON GEOTHERMAL ENERGY

Because of the scarcity of information on geothermal systems involving hot water or steam, a Geothermal Energy Project has been organized at Cornell to carry out analytical, numerical, and laboratory studies of these systems.

The project got under way in the spring of 1974, when funds for two geothermal energy traineeships were received from the National Science Foundation. These were awarded to Robert Ribondo, a graduate student in mechanical engineering, and Carl Sondergeld, a graduate student in geological sciences. The research of these students is also supported by a grant from the Engineering Division of the National Science Foundation.

Bob Ribondo is carrying out a series of numerical calculations of thermal convection in a porous medium under the supervision of Professor Kenneth E. Torrance of the Sibley School of Mechanical and Aerospace Engineering. Initially he carried out studies of single-phase flows of water in a porous layer heated from below, and subsequently he performed numerical calculations of thermal convection in a porous layer in which the water is allowed to enter and leave through the upper boundary. These results have been applied in studies of the oceanic crust, where the circulation of salt water may be important in the formation of mineral deposits.

Ribondo has also considered thermal convection in a porous media when the fluid and the matrix have different temperatures. The purpose of this study is to understand hot springs, and the results have been applied to the Steamboat Springs system just south of Reno in Nevada. Ribondo is also extending his studies to two-phase thermal convection.

Carl Sondergeld has built a simulation facility for two-phase thermal convection under my supervision. The facility (see the photograph) is known as a "sand box," but in this case is filled with small glass beads and distilled water. The box is heated from below with radiation heaters until the boiling temperature is reached, and cooled from above with a cooling coil; the temperature distribution is monitored with thermocouples. Without the porous matrix, simple boiling would take place. The porous matrix stabilizes the flow and steady thermal convection occurs. The upper part of the convecting layer is water below the boiling temperature and the lower part is a mixture of steam and water at the boiling temperature. Steam is produced at the lower boundary of the layer and condenses at the interface between the two-phase and water zones. The density difference between the water and water-steam mixture drives the convection. These studies have already led to new insights into the basic processes involved in two-phase thermal convection. They are a first step towards an understanding of the far more complex processes that are occurring in geothermal areas.

Donald L. Turcotte, a specialist in geomechanics and geophysical fluid dynamics, joined the Cornell Department of Geological Sciences in 1973 after fourteen years as a member of the aerospace engineering faculty. His interest in geological aspects of fluid dynamics began during a 1965–66 sabbatic leave at the University of Oxford, where he began a continuing collaboration with E. Ronald Oxburgh, a lecturer in geology. Turcotte has conducted research, including laboratory experiments, numerical modeling, and theoretical calculations, on thermal and fluid convection in the moon as well as in the earth's mantle. At the present time his research primarily concerns the state of stress and the thermal convection of fluids in the earth's crust.

Turcotte earned an undergraduate degree in mechanical engineering in 1954 and a doctorate in aerospace engineering in 1958 at the California Institute of Technology. He also received the Master of Engineering (Aerospace) degree from Cornell in 1955. Before joining the Cornell faculty, he served for a year as an assistant professor at the United States Naval Postgraduate School.

He is the author of Space Propulsion, *published by Blaisdell in 1965, and coauthor of* Statistical Thermodynamics, *published by Addison-Wesley in 1963, and has contributed many articles to professional journals. He is a fellow of the Geological Society of America and a member of the American Physical Society, the American Geophysical Union, and the Seismological Society of America.*

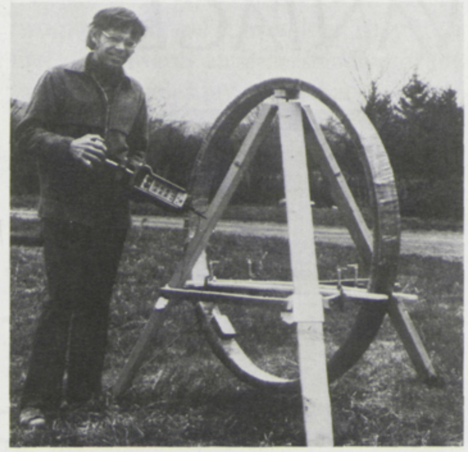
VANTAGE

Electrical Conductivity of Earth's Crust as an Indication of Geothermal Activity

A way of detecting geothermal activity in the earth's deep crust is being developed in a Cornell project under the direction of Arthur F. Kuckes, professor of applied physics. He and his graduate students are applying electromagnetic induction sounding techniques, developed in an earlier phase of the project, to map electrical conductivity of the earth's deep crust. Since electrical conductivity is a strong function of temperature, the measurements may be useful in locating deep pockets of magma, or "hot spots," as well as geothermal activity closer to the surface. The research may contribute also to an understanding of the basic tectonic processes involved in volcanism. The project has been funded by the National Science Foundation since 1973.

Crustal structure at depths to forty kilometers is being studied. The first measurements were made in certain igneous rock formations in the Adirondacks of New York State. Later studies are planned for the Snake River Plain region of the western United States, as part of the United States Geological Survey program to evaluate national geothermal resources.

Two graduate students working on the project spent six months last year in the Adirondacks, making magnetic field measurements. They are Anthony Nekut, shown at right with one of the portable recording units, and John Connerney, shown at far right with equipment at one of the field stations. The tent-like struc-



Right: Professor Kuckes, shown with an air-core coil used in magnetic field measurements, is currently on sabbatic leave. Graduate students Nekut and Connerney provided sketches illustrating the experiments in the Adirondacks.

The current loop (Figure 1) generates the source dipole field; vertical and horizontal magnetic field intensity measurements made at a remote site include a contribution due to currents induced in the conducting earth (represented by the small loop below the surface). Without such induced currents, no horizontal field would be measured, since the source field is vertical (see Figure 2). From the magnetic fields measured at the earth's surface, one can learn about the electrical conductivity of the earth as a function of depth.

Figure 1

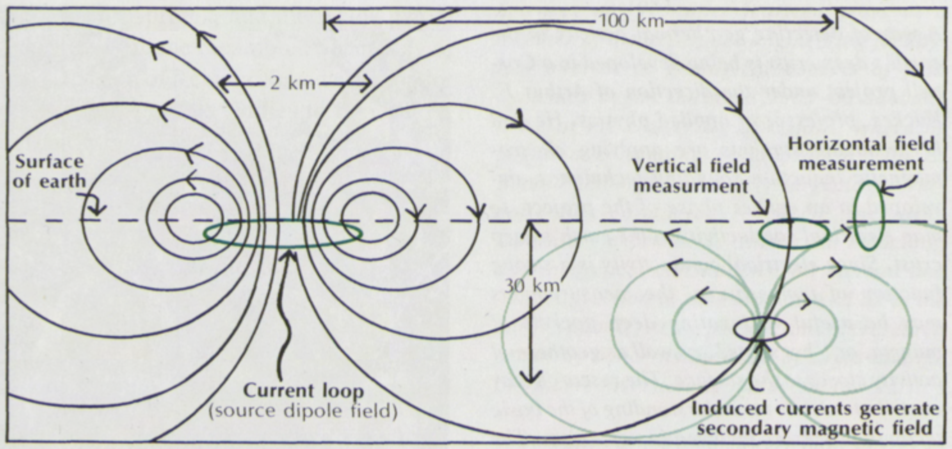
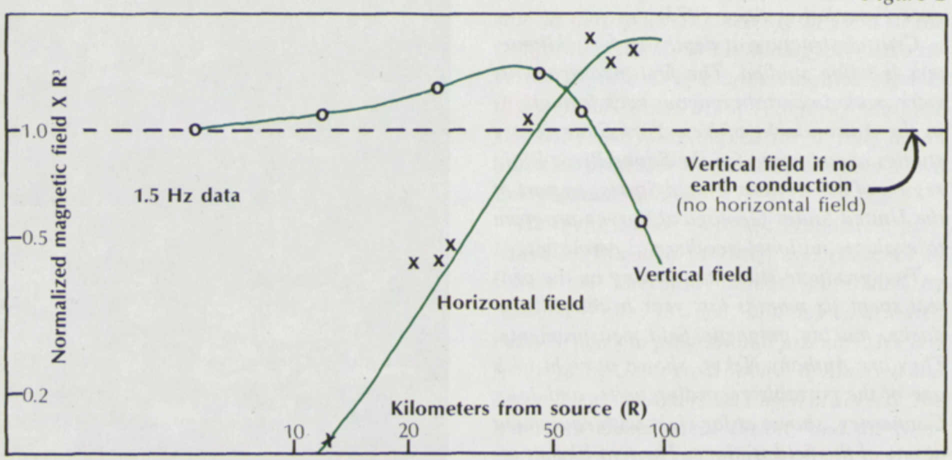


Figure 2



ture in the background protects an iron-core pick-up coil.

The equipment, designed and built by the researchers, measures and records the magnetic field strength at several discrete frequencies in the range of 0.4 to 400 cycles per second. Subsequent signal averaging of data acquired over a period of weeks reduces the uncorrelated magnetic field fluctuations (noise) and permits the retrieval of a source-correlated field (signal). The signal strength is typically a billion times smaller than the earth's dipole field.

The source of the signal is a time-varying magnetic dipole generated by electrical currents in a wire loop two kilometers in diameter. This is installed near the Adirondack village of Newcomb on land of the Huntington Forest Ecological Station, which is maintained by Syracuse University. The data were collected at five stations set up along a ninety-kilometer stretch between Newcomb and Potsdam.

While in the Adirondacks, Nekut and Connerney stayed at a Cornell-owned cabin in Newcomb and spent much of their time servicing the equipment and replacing cassette tapes. This required making trips of one hundred fifty miles or so every other day, often over snow-covered mountain roads. Back at the cabin, they analyzed the data on a computer they had brought along. They are spending the spring term on campus, completing analyses and interpretation of the measurements.

FACULTY PUBLICATIONS

The following publications and conference papers by faculty members and graduate students of the Cornell College of Engineering were published or presented during the period August through October 1975. Earlier publications inadvertently omitted from previous listings are included here with the date in parentheses. The names of Cornell personnel are in italics.

■ AGRICULTURAL ENGINEERING

Albright, L. D. 1975. Air Moving Efficiencies of Ventilating Fans. Paper read at North Atlantic Regional Meeting of the American Society of Agricultural Engineers, 17-20 August 1975, at Cornell University, Ithaca, New York.

Coote, D. R.; *Haith, D. A.*; and *Zwerman, P. J.* 1975. The environmental and economic impact of nutrient management on the New York dairy farm. *Search* 5 (5): 1-28.

Haith, D. A. 1975. Integrated systems for power plant cooling and wastewater management. In *Energy, agriculture, and waste management*, ed. W. J. Jewell, pp. 219-236. Ann Arbor, Michigan: Ann Arbor Science.

Jewell, W. J., and *Loehr, R. C.* 1975. Energy Recovery from Animal Wastes: Anaerobic Digestion, Pyrolysis, Hydrogenation. Paper read at International Seminar on Animal Wastes (sponsored by the World Health Organization and the Czechoslovak Centre for Environmental Pollution Control), 28 September – 5 October 1975, in Bratislava, Czechoslovakia.

Loehr, R. C. 1975. Nutrient Control Applicable to Animal Wastes. Paper read at International Seminar on Animal Wastes, 28 September – 5 October 1975, in Bratislava, Czechoslovakia.

Loehr, R. C., and Denit, J. D. 1975. Effluent Regulations for Animal Feedlots. Paper read at International Seminar on Animal Wastes, 28 September – 5 October 1975 in Bratislava, Czechoslovakia.

Lorenzen, R. T.; *Black, R. D.*; and *Nieber, J. L.* 1975. Design Aspects of Buildings for Flood Plain Locations. Paper read at 1975 Annual Meeting of the American Society of Agricultural Engineers, 22-25 June 1975, at the University of California, Davis, California.

Rehkugler, G. E., and *Throop, J. A.* 1975. Optical-mechanical bruised apple sorters. In *Quality detection in foods*, ASAE publication I-76. St. Joseph, Michigan: American Society of Agricultural Engineers.

■ APPLIED AND ENGINEERING PHYSICS

Fertuck, H.C.; *Woodward, W. W.*, and *Salpeter, M. M.* 1975. In vivo recovery of muscle contraction after α-Bungarotoxin binding. *Journal of Cell Biology* 66:209-213.

Chen, C. H., and *Silcox, J.* 1975. Detection of optical surface guided modes in thin graphite films by high-energy electron scattering. *Physical Review Letters* 35(6):390-393.

______. 1975. Surface guided modes in an aluminum oxide thin film. *Solid State Communications* 17:273-275.

Chen, C. H.; *Silcox, J.*; and *Vincent, R.* (1975). Electron-energy losses in silicon: bulk and surface plasmons and Cerenkov radiation. *Physical Review B* 12(1):64-71.

Pettit, R. B.; *Silcox, J.*; and *Vincent, R.* (1975). Measurement of surface-plasmon dispersion in oxidized aluminum films. *Physical Review B* 11(8):3116-3123.

Silcox, J. 1975. Oxide Structures in Evaporated Al Films. Paper read at Gordon Research Conference on Thin Films and Solid Surfaces, 18-22 August 1975, at Proctor Academy, Andover, New Hampshire.

■ CHEMICAL ENGINEERING

Benis, A.M.; Nossel, H. L.; Aledort, L. M.; Koffsky, R. M.; *Stevenson, J. F.*; Leonard, E. F.; Shiang, H.; and Litwak, R. S. 1975. Extracorporeal model for study of factors affecting thrombus formation. *Thrombosis et Diathesis Haemorrhagica* 34:127-144.

Chung, S. C.-K, and *Stevenson, J. F.* 1975. A general elongational flow experiment: inflation and extension of a viscoelastic tube. *Rheologica Acta* 14:832-841.

Harriott, P. 1975. Thermal conductivity of catalyst pellets and other porous particles. Part I: Review of models and published results. *Chemical Engineering Journal* 10:65-71.

Quinn, J. A.; Steinbrook, R. A.; and *Anderson, J. L.* 1975. Breaking bubbles and the water-to-air transport of particulate matter. *Chemical Engineering Science* 30:1177-1184.

Sharma, C. S.; *Harriott, P.*; and Hughes, R. 1975. Thermal conductivity of catalyst pellets and other porous particles. Part II: Experimental measurements. *Chemical Engineering Journal* 10:73-80.

Stevenson, J. F.; Chung, S. C.-K; and *Jenkins, J. T.* 1975. Evaluation of material functions for steady elongational flows. *Transactions of the Society for Rheology* 19:397-405.

Yu, H., and *Scheele, G. F.* 1975. Laminar jet contraction and velocity distribution in immiscible liquid-liquid systems. *International Journal of Multiphase Flow* 2:153-169.

■ CIVIL AND ENVIRONMENTAL ENGINEERING

Brutsaert, W. 1975. On a derivable formula for long-wave radiation from clear skies. *Water Resources Research* 11(5):742–744.

______ . 1975. The roughness length for water vapor, sensible heat, and other scalars. *Journal of the Atmospheric Sciences* 32 (10):2028–2031.

______ . 1975. A theory for local evaporation (or heat transfer) from rough and smooth surfaces at ground level. *Water Resources Research* 11(4):543–550.

Cesario, F. J. 1975. A combined trip generation and distribution model. *Transportation Science* 9:211–233.

______ . 1975. Emissions implications of traffic reductions. *Journal of the Air Pollution Control Association* 25:957–958.

______ . 1975. The Energy-Environment-Transportation Interface. Relationships Amongst Energy, People Movements, and Goods Movements. Papers read at Union College Technical Institute Program on Effects of Energy Constraints on Transportation Systems, 4–8 August 1975, in Schenectady, New York.

______ . 1975. Environmental-energy policies and automotive pollution. *Journal of Environmental Systems* 5:13–28.

Gallagher, R. H. 1975. Shell elements. In *Proceedings of the world congress on finite element methods in structural mechanics*, ed. J. Robinson, vol. 1, pp. E.1–E.25. Dorset, England: Robinson.

Grosskurth, J. F.; *White, R. N.; Gallagher, R. H.*; and Thomas, G. 1975. *Shear buckling of perforated plates*. NASA report CR 132548.

Kay, J. N. 1975. Interlock tension in steel sheet piling. *Proceedings of the ASCE, Journal of the Structural Division* 101(ST10):2093–2101.

______ . 1975. A probabilistic approach to the design of sheet pile cofferdams. In *Proceedings of 2nd international conference on the applications of statistics and probability to soil and structural engineering*, pp. 131–141. Aachen, Germany.

Liu, P. L.-F., and Mei, C. C. 1975. *Effects of a breakwater on nearshore currents due to breaking waves*. Technical memorandum no. 57, U.S. Army Corps of Engineers, Coastal Engineering Research Center.

Sangrey, D. A.; Murphy, J. J. ; and *Nieber, J. L.* 1975. *Evaluating the impact of structurally interrupted flood plain flows*. Technical report 98, Cornell University Water Resources and Marine Sciences Center.

Sangrey, D. A.; Teng, W. L.; Philipson, W.; and *Liang. T.* 1975. Remote sensing of ground and surface waters contaminated by leachate from landfill. In *Proceedings of the international conference on environmental sensing and assessment* (September 1975, in Las Vegas, Nevada). New York: Institute of Electrical & Electronics Engineers and Society of Photographic Scientists and Engineers.

Stopher, P. R., and *Meyburg, A. H.* 1975. *Urban transportation modeling and planning*. Lexington, Massachusetts: Lexington Books, D. C. Heath.

White, R. N., et al. 1975. *Interim storage of solidified high-level radioactive wastes*. Publication of the Panel on Engineered Storage, Committee on Radioactive Waste Management, National Academy of Sciences.

______ . 1975. Reinforced concrete hyperbolic paraboloid shells. *Proceedings of the ASCE, Journal of the Structural Division* 101(ST9):1961–1980.

Willis, R. 1975. Optimal Management of the Subsurface Environment. Paper read at International Symposium on the Geochemistry of Natural Waters, 18–22 August 1975, in Burlington, Ontario, Canada.

■ COMPUTER SCIENCE

Hopcroft, J.; Paul, W.; and Valiant, L. 1975. On time versus space and related problems. In *Proceedings of 16th annual symposium on foundations of computer science*, pp. 57–63. New York: Institute of Electrical & Electronics Engineers.

Williams, J. H. 1975. Bounded context parsable grammars. *Information and control* 28(4):314–334.

■ ELECTRICAL ENGINEERING

Antonsen, T. M., Jr., and *Ott, E.* 1975. Velocity shear driven instabilities of an unneutralized electron beam. *Physics of Fluids* 18(9):1197–1208.

Bahrami, K., and *Kim, M.* 1975. Optimal control of multiplicative control systems arising from cancer therapy. *IEEE Transactions on Automatic Control* AC–20:537–542.

______ . 1975. Modeling the effect of cell specific drugs on a cell population. In *Proceedings of 28th annual conference on engineering in medicine and biology*, vol. 15, p. 89. New Orleans, Louisiana: Alliance for Engineering in Medicine and Biology.

Berger, T. 1975. Information-singular random processes. *IEEE Transactions on Information Theory* IT–21:502–511.

Camp, W. O., and *Eastman, L. F.* 1975. The limits on doping concentration to frequency ratio as a function of temperature and doping profile in T.E.O. In *Proceedings of 5th biennial Cornell electrical engineering conference: Active semiconductor devices for microwaves and integrated optics*, pp. 205–213. Ithaca, New York: Cornell University.

Capranica, R. R., and *Moffat, A. J. M.* 1975. Selectivity of the peripheral auditory system of spadefoot toads (*Scaphiopus couchi*) for sounds of biological significance. *Journal of Comparative Physiology* 100:231–249.

Chan, V. W. S. 1975. *Characterization of measurements in quantum communications*. Report TR 489, Research Laboratory of Electronics, Massachusetts Institute of Technology.

Eastman, L. 1975. Microwave Semiconductor Materials Research at Cornell University. Paper read at Seminar at Varian Associates, 13 October 1975, in Palo Alto, California.

Farley, D. T., and Fejer, B. G. 1975. The effect of the gradient drift term on type 1 electrojet irregularities. *Journal of Geophysical Research* 80:3087–3090.

Feng, A. S.; Narins, P. M.; and *Capranica, R. R.* 1975. Three populations of primary auditory fibers in the bullfrog (*Rana catesbeiana*): their peripheral origins and frequency sensitivities. *Journal of Comparative Physiology* 100:221–229.

Frey, J., and *Bowers, R.* 1975. The impact of solid state microwave devices: a preliminary technology assessment. In *Advances in electronics and electron physics*, vol. 38, pp. 147–194. New York: Academic Press.

Frey, J., and *Maloney, T. J.* 1975. Limits on noise performance of GaAs and InP FETs. In *Proceedings of 5th biennial Cornell electrical engineering conference: Active semiconductor devices for microwaves and integrated optics*, pp. 277–285. Ithaca, New York: Cornell University.

Kelley, M. C., et al. 1975. Electric field measurements in a major magnetospheric substorm. *Journal of Geophysical Research* 80(22):3181–3195.

Kelley, M. C., and Mozer, F. 1975. Simultaneous measurement of the horizontal components of the earth's electric field in the atmosphere and in the ionosphere. *Journal of Geophysical Research* 80(22):3275–3276.

Kim, M. 1975. Observability for identification of cancer cell cycle and proliferative kinetic state. *Proceedings of the IEEE* 63:986–988.

Kim, M., and Park, C. M. 1975. Algorithms for machine recognition, noise cleaning and thinning of the Korean characters. In *Proceedings of international computer symposium*, ed. C. L. Sheng, pp. 513–520. Taipei, Taiwan: National Chiao Tung University.

Klein, H. H.; *Ott, E.;* and Manheimer, W. M. 1975. The effect of trapping on the saturation of the Raman backscatter instability. *Physics of Fluids* 18(8):1031–1033.

Lawrence, D., and *Eastman, L. F.* 1975. Electric current controlled growth and doping modulation in GaAs liquid phase epitaxy. *Journal of Crystal Growth* 30:267–275.

______ . 1975. Electric Current Controlled LPE Growth of GaAs. Paper read at Seminar at IBM Research Laboratory, 11 August 1975, in Yorktown, New York.

Linke, S. 1975. *Preliminary transmission analysis for a hypothetical nuclear energy center in New Jersey.* In report BNL 50465, Brookhaven National Laboratory Regional Energy Studies Program.

McFarlane, R. A. 1975. Microwave discharge atom source for chemical lasers. *Review of Scientific Instruments* 46:1063–1065.

Mikkelsen, I; Jorgensen, T.; and *Kelley, M. C.* 1975. Observation and interpretation of plasma motions in the polar cap ionosphere during magnetic substorms. *Journal of Geophysical Research* 80(22):3197–3204.

Ott, E., and *Farley, D. T.* 1975. Microinstabilities and the Production of Short Wavelength Irregularities in the Equatorial F Region. Paper read at URSI General Assembly, August 1975, in Lima, Peru.

Ott, E., and *Lovelace, R. V.* 1975. Magnetic insulation and microwave generation. *Applied Physics Letters* 27(7):378–380.

Pirkle, R. J.; Davis, C. C.; and *McFarlane, R. A.* 1975. Self-mode-locking of an iodine photodissociation laser. *Journal of Applied Physics* 46:4083–4085.

Pirkle, R. J.; Wiesenfeld, J. R.; Davis, C. C.; Wolga, G. J.; and *McFarlane, R. A.* 1975. Production of electronically excited iodine atoms, $I^2P\frac{1}{2}$, following injection of HI into a flow of discharged oxygen. *IEEE Journal of Quantum Electronics* QE–11(10):834–838.

Turner, J.; Moses, E.; and *Tang, C. L.* 1975. Spectral narrowing and electro-optic tuning of pulsed dye lasers by injection-locking to a CW dye laser. *Applied Physics Letters* 27:441–443.

■ GEOLOGICAL SCIENCES

Bloom, A. L. (1975). Sea-level movements during the last deglacial hemicycle (about 15,000 years). *Association Sénégalaise pour l'étude du Quaternaire de l'ouest-Africain* 44–45:25–31.

Cisne, J. L. (1975). Anatomy of *Triarthrus* and the relationships of the Trilobita. *Fossils and Strata* 4:45–63.

Clark, S. P.; *Turcotte, D. L.;* and *Nordmann, J. C.* 1975. Accretional capture of the moon. *Nature* 258:219–220.

Oliver, J. 1975. Beiträge der Seismologie zur Plattentektonik (German translation of "Contributions of seismology to plate tectonics," *AAPG Bulletin* 56:214:225). In *Die Entstehung der Kontinente und Oceane in heutiger Sicht*, ed. R. Schonenberg, pp. 168–185. Darmstadt, West Germany: Wissenschaftliche Buchgesellschaft.

Parmentier, E. M.; Turcotte, D. L.; and *Torrance, K. E.* 1975. Numerical experiments on the structure of mantle plumes. *Journal of Geophysical Research* 80:4417–4424.

■ MATERIALS SCIENCE AND ENGINEERING

Blakely, J. M. 1975. *Surface physics of materials*, vols. I and II. New York: Academic Press.

Goldfarb, W.; Krakow, W.; *Ast, D.;* and *Siegel, B.* 1975. Imaging of amorphous objects by tilted beam bright field illumination. In *33rd annual proceedings of the Electron Microscopy Society of America*, ed. E. W. Bailey, pp. 186–187. Baton Rouge: Claitor's Publishing Division.

Hall, T. M.; Wagner, A.; Berger, A. S.; and *Seidman, D. N.* 1975. A Time-of-Flight Atom-Probe Field-Ion Microscope for the Study of Defects in Metals. Paper read at 22nd International Field Emission Symposium, 25–29 August 1975, at Georgia Institute of Technology, Atlanta, Georgia.

Kohlstedt, D. L., and Van der Sande, J. B. 1975. An electron microscopy study of naturally occurring oxidation precipitates in iron-bearing olivines. *Contributions to Mineralogy and Petrology* 53:13–24.

Kramer, E. J. 1975. Microstructure-critical current relationships in hard superconductors. *Journal of Electronic Materials* 4:839–881.

Kramer, E. J., and Knapp, G. S. 1975. The anisotropy of H_{c2} and its implications to grain-boundary flux pinning in V_3Si. *Journal of Applied Physics* 46:4595–4596.

Krenz, H. G.; Kramer, E. J.; and *Ast, D. G.* 1975. Direct measurements of the strain energy release rate of propagating crazes by holographic interferometry. *Journal of Polymer Science—Polymer Letters* 13:583–587.

Kuan, T. S.; Ahrens, R. R.; and *Sass. S. L.* The stress-induced omega phase transformation in Ti-V alloys. *Metallurgical Transactions A* 6A:1767–1774.

Raj, R. 1975. Transient behavior of diffusion induced creep and creep rupture. *Metallurgical Transactions A* 6A:1499–1509.

Sachse, W. 1975. On the measuring and recording of transient phenomena in vibrating systems. *Review of Scientific Instruments* 46:1352–1355.

Sachse, W., and *Ruoff, A. L.* 1975. Elastic moduli of precompressed pyrophyllite used in ultrahigh-pressure research. *Journal of Applied Physics* 46:3725–3730.

Schwartz, A.; Stenzel, K. H.; Kohno, I; *Ast, D.;* Miyata, T.; and *Rubin, A. L.* 1975. Deposition of blood cells on collagen and cuprophane membranes. *Journal of Biomedical Materials Research* 9:453–463.

Seidman, D. L. 1975. The study of Point Defects in Irradiated or Quenched Metals by Quantitative Atom-Probe and Field-Ion Microscopy. Paper read at 22nd International Field Emission Symposium, 25–29 August 1975, at Georgia Institute of Technology, Atlanta, Georgia.

______ . 1975. The Study of Stages I to IV of Irradiated or Quenched Tungsten and Tungsten Alloys by Field-Ion Microscopy. Paper read at Japan-America Symposium on Radiation Damage in Metals, 28–30 September 1975, at Iowa State University, Ames, Iowa.

Seidman, D. N., et al. 1975. Report to the APS by the study group on physics problems relating to energy technologies: Radiation effects on materials. *Reviews of Modern Physics* 47 (supplement 3): S1–44.

Seidman, D. N.; Wilson, K. L.; and *Nielsen, C. H.* 1975. Comment on "Free migration of interstitials in tungsten." *Physical Review Letters* 35:1041–1042.

Viswanadham, R. K., and *Kramer, E. J.* 1975. Structure of reconstituted collagen hollow fiber membranes. *Journal of Materials Science* 10:1472–1480.

Wagner, A.; Hall, T. M.; and *Seidman, D. N.* 1975. Simplified method for the calibration of an atom-probe field-ion microscope. *Review of Scientific Instruments* 46:1032–1034.

■ MECHANICAL AND AEROSPACE ENGINEERING

Auer, P. L. 1975. Illusions and Realities in Energy Policy Development. Paper read at Cornell-Carleton Conference on North American Energy Policy, 2–4 October 1975, at Carleton University, Ottawa, Canada.

Bartel, D. L.; Dueland, R. T.; and *Quenin, J. A.* 1975. Biomechanical considerations in the design of a canine total hip prosthesis. *Journal of the American Animal Hospital Association* 11(5):553–559.

George, A. R.; Kim, Y. N.; and *Kitaplioglu, C.* 1975. Rotor Noise from Random Loadings and from High Tip Speeds. Paper read at Helicopter and V/STOL Aircraft Research Conference, 7–8 October 1975, at NASA Ames Research Center, Moffett Field, California.

Gutman, D. P., and *Torrance, K. E.* 1975. Response of the urban boundary layer to heat addition and surface roughness. *Boundary-Layer Meteorology* 9:217–233.

Leibovich, S. 1975. A Theory of the Ocean Wind-Drift Current. Paper read at Department of Theoretical Physics and Applied Mathematics Seminar, 18 September 1975, at the University of Cambridge, Cambridge, England.

______ . 1975. Vortex Breakdown: Experiment and Theory. Paper read at 12th Biennial Symposium on Advanced Problems and Methods in Fluid Dynamics, 8-13 September 1975, in Bialowieza, Poland.

Lung, J. L.; Tiegerman, B.; Yu, N. J.; and *Seebass, A. R.* 1975. Advances in sonic boom theory. In *Aerodynamic analysis requiring advanced computers,* Part II, pp. 1033–1048. NASA publication SP–347.

McLean, W. J.; de Boer, P. C. T.; Homan, H. S.; and *Fagelson, J. J.* 1975. Hydrogen as a reciprocating engine fuel. In *Proceedings of the symposium on future automotive fuels.* Warren, Michigan: General Motors Corporation.

Miller, C. W., and *Resler, E. L., Jr.* 1975. Magnetic forces and the surface instability in ferromagnetic fluids. *Physics of Fluids* 18(9):1112–1118.

Radulovic, P. T., and Vest, C. M. 1975. Direct three-dimensional reconstruction. In *Image processing for 2-D and 3-D reconstruction from projections: Theory and practice in medicine and the physical sciences,* pp. TuD1–TuD4. Stanford, California: Optical Society of America.

Rubin, M. B., and *McLean, W. J.* 1975. Analysis of Methanol as a Reciprocating Engine Fuel. Paper read at Fall Meeting, Western States Section, The Combustion Institute, 29 October 1975, at Stanford Research Institute, Menlo Park, California.

Stevenson, J. F.; Hieber, C. A.; Wang, K. K.; and *Galskoy, A.* 1975. An Experimental Study and Simulation of Disk Filling by Injection Molding. Paper read at 46th Annual Meeting of the Society of Rheology, 27–30 October 1975, in St. Louis, Missouri.

Thompson, W. P., and *De Boer, P. C. T.* 1975. Ion density measurements with an electric probe. *AIAA Journal* 13(8):1115–1117.

Torrance, K. E., and *Mahajan, R. L.* 1975. Surface tension flows induced by a moving thermal source. *Combustion Science and Technology* 10:125–136.

Vest, C. M., and *Radulovic, P. T.* 1975. *Quantitative interpretation of multi-directional holographic interferometry.* Office of Naval Research report no. INTFL–7501.

■ THEORETICAL AND APPLIED MECHANICS

Conway, H. D., and Lee, H. C. 1975. The analysis of the lubrication of a flexible journal bearing. *Journal of Lubrication Technology* 97:599–604.

______ . 1975. Impact of a lubricated surface by a sphere. *Journal of Lubrication Technology* 97:613–615.

Jenkins, J. T. 1975. Static equilibrium of granular materials. *Journal of Applied Mechanics* 42:603–606.

Mukherjee, S. 1975. Variational principles for waves in periodic viscoelastic composites. In *Proceedings of 12th annual meeting of the Society of Engineering Science,* ed. M. Stern, pp. 519–528. Austin, Texas: University of Texas at Austin.

Varatharajulu, V. K., and *Mukherjee, S.* 1975. On crack velocity in composites. In *Proceedings of 12th annual meeting of the Society of Engineering Science,* ed. M. Stern, pp. 1305–1314. Austin, Texas: University of Texas at Austin.

■ GENERAL

Ott, M. D. 1975. Observations of audio-tutorial learning center activities. *Educational Technology* 15:46–49.

Engineering: Cornell Quarterly

Published by the College of Engineering, Cornell University
Edmund T. Cranch, Dean

Editor: Gladys McConkey

Circulation Manager: Janice Skelton

Graphic Art Work: Francis Russell

Lithographers: General Offset Printing Co., Springfield, Massachusetts

Typography: Eastern Photocomp, Hartford, Connecticut 06103

Photo credits for this issue are as follows:
John Connerney: 35 (left)
Daniel Karig, Greg Moore, and associates: 26, 27
Anthony Nekut: 35 (right)
David Ruether: 1, 10, 20, 29, 33, inside back cover

Please address any correspondence, including notification of change of address, to ENGINEERING: Cornell Quarterly, Carpenter Hall, Ithaca, New York 14853.

ENGINEERING
Cornell Quarterly
Carpenter Hall, Ithaca, N. Y. 14853

Return postage guaranteed

Second Class
Postage Paid at
Ithaca, N. Y. 14853