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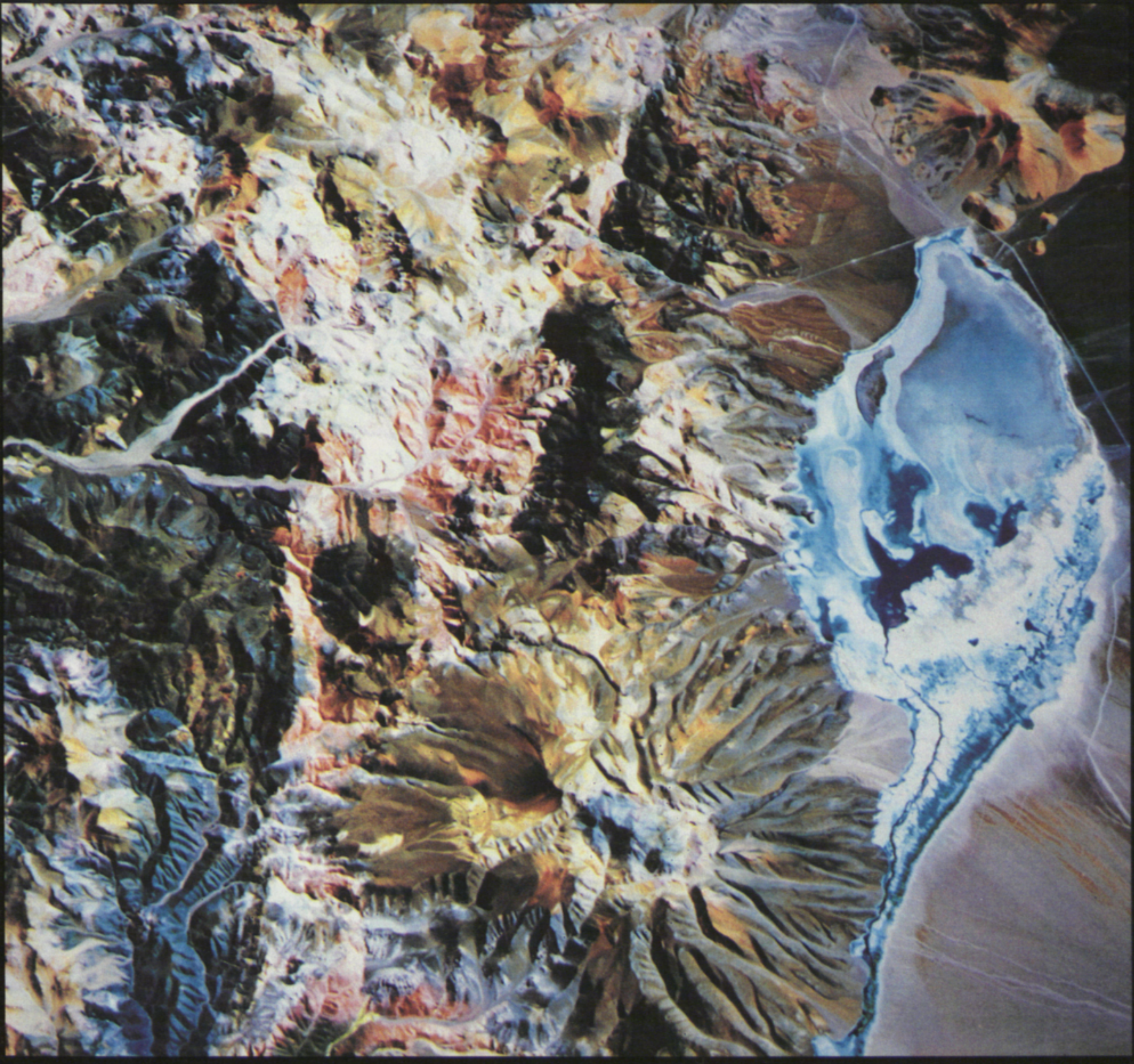

PROBING EARTH'S PROCESSES

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Cover: a false-color Thematic Mapper satellite image showing the western edge of the Chilean Puna at about 27° south. Maricunga Volcano is at lower center. The large blue area, in the rain shadow of the high mountains, is the Salar de Maricunga.

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PROBING EARTH'S PROCESSES

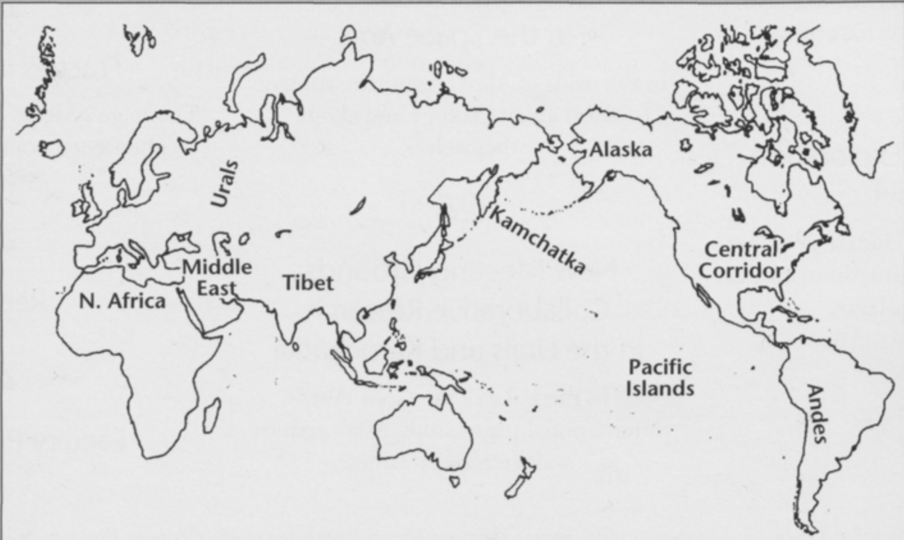
Geologists interpret contemporary evidence to understand processes that have shaped the earth over the course of its four-and-a-half-billion-year history. The clues they have to work from are often very subtle because residual evidence of early processes may be obscured by later processes, and ongoing processes that happen over millions of years are virtually imperceptible in human lifetimes. But a number of technological advances have made it possible to detect these subtle clues. Satellites can map and measure the entire surface of the earth; deep seismic profiling can discern geologic features far below the surface; geochemical techniques can measure trace elements in the parts-per-billion range; and computers can manipulate and synthesize vast amounts of data.

The rapid development of the earth sciences has come about through research that is broadly interdisciplinary. Plate movements and mantle plumes are understood in terms of physics, and many processes are modeled mathematically. Chemistry is indispensable for many branches of geology. Important interactions link geological and meteorological phenomena, and even biological systems affect and are affected by what happens to the solid earth.

This sophisticated, multidisciplinary research is helping geologists develop an understanding of many of the processes that have led to observed structural regularities. The way seas open and close, the way mountains rise and are worn down, and the way minerals are segregated and dispersed are increasingly well understood. Building on the patient description and classification of past generations, modern geologists with space-age technology are making their science explanatory and predictive.

What they are learning is of immense practical value. As the human population grows larger and larger, it places ever greater pressures on the earth. Geologists can help find new supplies of mineral resources, new ways to exploit low-grade resources, and new substitutes for old resources. They can also help assess the likely consequences of anthropogenic changes to planetary systems by examining how the earth has responded to similar stresses in the past. For better or worse, intentionally or unintentionally, human beings are changing the face of the planet—and many changes will be engineered and monitored by geologists.

This issue of the *Quarterly* describes some of the research that is being conducted in the Department of Geological Sciences at Cornell. Projects are afoot in the Andes of South America, in the Himalayas of Tibet, in North Africa and the Middle East, in Alaska and the former Soviet Union, in the islands of the Pacific Ocean, and in the Central Corridor of North America. Interests range from magmatic material that may have welled up from near the earth's core to erosional debris that has washed down from the earth's highest mountains. This brief treatment cannot hope to portray the full scope of research conducted in the Department of Geological Sciences, but it does suggest the geographic breadth and topical diversity of work by a talented faculty dedicated to learning more about the earth's processes.—DP



Research activities are worldwide.

MOUNTAINS, CLIMATE, AND GLOBAL CHANGE

by Bryan L. Isacks

Processes that shape the surface of the earth involve a complex interplay among rock, water, air, and living organisms. A growing awareness of how much these different realms influence each other is promoting a revolutionary integration of geology and other fields such as atmospheric sciences, hydrology, oceanography, and biology. The neat divisions between traditional disciplines have proven an obstacle to understanding the highly integrative, nonlinear systems that are beginning to emerge. In consequence, a new, open-ended, interdisciplinary approach is taking shape.

During the mid-1980s, members of the Cornell Andes Project won grants from the National Aeronautics and Space Administration (NASA) to acquire and study satellite images of the Andes. The collection of Landsat Thematic Mapper images now covers the entire central Andes of southern Peru, Bolivia, and northern Chile and Argentina. To help analyze this data, the project also acquired what has become one of the most powerful computer systems on campus. Large sets of digital geological and topographic data were developed, and the first regional topographic image of the central Andes was produced.

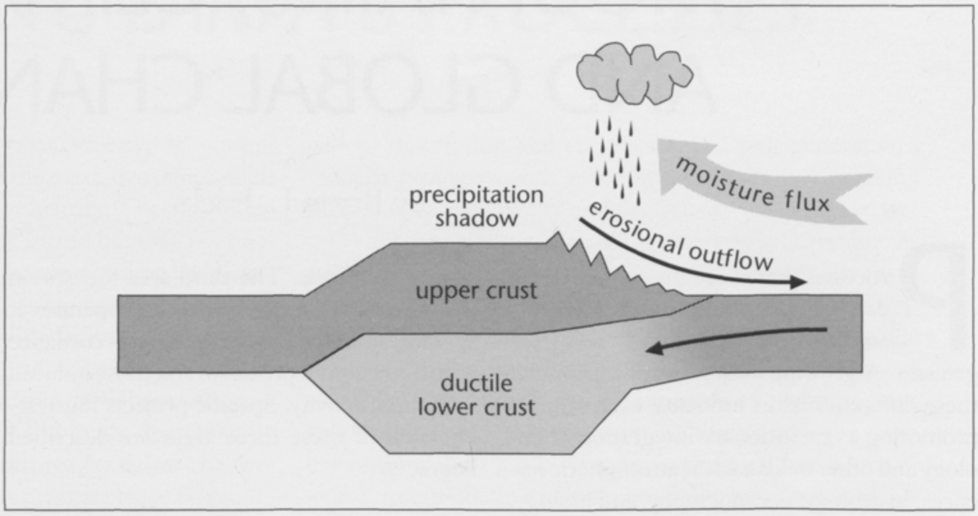
This material opened up a completely new and unprecedented view of mountain belts that dramatically emphasizes the earth's surface as a highly complex zone of interactions between the solid earth and the atmosphere. Over the years, three closely related research areas, which differ in the time scale of what they study, have developed. The first, which focuses on the evolution of mountain belts, deals in millions to tens of millions of years. During these great spans of time, cyclical ice ages stand out as the most important feature of climate-mountain interaction. The second area of research zooms in to examine the most recent ice age and the profound changes in climate that have occurred since that time, which provide climate modelers with the best test of their predictive efforts. The third area focuses on the mountain/climate system as it operates at present, and how it is changing in accordance with both natural processes and those induced by human activity. Specific projects illustrating each of these three areas are described below.

Mountain Belts As Erosional Machines

A research initiative in which I am involved, along with Associate Professor Teresa Jordan, research associate Eric Fielding, and graduate students Jeffrey Masek and Christopher Duncan, involves looking at the earth's mountain belts in terms of both the internal process of crustal thickening and the climate-driven processes of erosion. When the earth's crust is thickened by deformation or volcanism, it floats high in hydrostatic or isostatic equilibrium on the denser substrate of underlying mantle. The height of the mountain surface provides the potential energy for water to do its erosional work on the landscape. In an actively growing mountain belt such as the Andes or the Himalayas, the mountains affect climate by focusing precipitation along one side of the belt, which skews the effects of erosion. When moist air flows toward the mountain belt, as it does in the Amazonian headwaters on the eastern side of the Andes and along the Himalayan edge of the Tibetan plateau during the monsoon, the upward movement caused by the topography causes the moisture to condense, producing a band of intense precipitation. This precipitation is most concentrated where the slope is steepest, which maximizes the ability of the erosional process to carry mass away from the mountain belt. Indeed, this combination of circumstances can produce the world's highest rates of erosion. We are now looking into the exciting possibility that these high erosion rates may control the nature and rate of the deformational processes causing the uplift, so that the interaction of mountain belts

"the earth's surface [is] a highly complex zone of interactions between the solid earth and the atmosphere."

Figure 1. A schematic view of the mountain-belt erosional machine. Crustal mass flows into the mountain belt, thickens the crust, and lifts the mountains. Moisture-laden warm air rises as prevailing winds carrry it over the mountains, causing precipitation that erodes one side of the range, while leaving a rain shadow on the other side.



and global circulation results in a self-maintaining processing machine that transforms large quantities of material from crustal rock into the dissolved and fragmentary material in oceans and sediments (Figure 1).

Research in this area exploits digital topographic, satellite, and climatic data sets that we are acquiring for the Andes, central Asia, and other areas of the world, such as New Zealand, Taiwan, and New Guinea, where mountain belts are associated with high precipitation rate. We analyze the topographic data as a two-dimensional spatial signal of both mountain-building processes and erosional processes. The erosional processes dominate at short wavelengths—the ravines and ridges of the drainage networks—and the mountain-building processes hidden beneath this erosional signal predominate at longer wavelengths. We are beginning to recognize distinctive quantitative topographic characteristics of the major processes and rates of mass movement, which occur through rainfall-induced landslides at lower elevations or glacial processes higher up.

To understand how the erosional machine works and how the topographic characteristics are to be interpreted, we are developing computer simulations by combining a simple crustal deformation model, a model for the topographic effect of precipitation, and a cellular-automaton model for the complex process of erosion by river networks. Our first results show clearly how precipitation and erosion are focused by the mountain-building process. They also lend strong support to the hypothesis that this complex constitutes a self-perpetuating machine.

Interpreting Evidence from the Last Ice Age

One of the most striking characteristics of the high-erosion zones on the slopes of the Andes and the Himalayas is the transition from a low-elevation regime where precipitation is in the form of rainfall to a high-elevation regime where snow predominates. More water falls as rain than as snow, but it runs off right away. The water in snow, on the other hand, is stored up for a time and then released rapidly. Spring runoff is characteristic of mountain drainage basins, and melting during rapid deglaciations in the ice age cycles may produce analogous periods of major runoff and erosion. During ice ages, when snow cover was more extensive, substantial amounts of erosion were caused by ice fields and glaciers as well as by freeze-thaw processes at the periphery of snow-covered regions.

The elevation above which perennial snow cover exists—the snow line so characteristic of high mountainous regions—is determined by the way temperature and precipitation vary. Both are functions of elevation and the complex interaction of regional climate and topography. The net result of climate change is an alteration in the elevation of the snow line. The area covered by perennial snow is related to the snow line in a way that is highly nonlinear, so the raising and lowering of the snow line during ice-age cycles can profoundly affect the erosional and hydrological regimes.

Opposite page: A scene in the Cordillera Real, near La Paz, Bolivia, showing the intimate relation between water (in three phases) and the solid earth.

Evidence showing the elevation of the snow line during the last ice age is well preserved in many mountain belts. This makes it possible to study the effects of heavy snow cover on the erosional system and also provides a major source of new information about climate during the ice age. These topics provide incredible research opportunities, and graduate student Andrew Fox, Professor Arthur Bloom, and I are working through Cornell's extensive library of satellite images of the central Andes to produce a comprehensive picture of ice-age snow lines. These can be inferred from residual evidence such as glacial cirques and moraines, which can be seen clearly in Landsat Thematic Mapper images. Fox's thesis research established the spatial pattern of snow-line lowering during the last ice age, making it possible to calculate that the average temperature at high elevations was nearly 10°C lower than at present. These findings present a major challenge to accepted ideas about ice-age climate in tropical regions.

Watching the Snow Line for Evidence of Climate Change

Fox's work compares ice-age climate with present climate. How do we know the present climate in the Andes? Weather stations operated by South American countries during this century provide the basic data, but these stations are distributed very sparsely over vast, remote regions and tend to be concentrated near airports and agricultural developments. Thus, the data give little information on the most rugged regions, where spatial variations in climate are greatest. Unfortunately, it is in just these regions that climate change can be expected to have the most profound effects. Glacial recession, which has been associated with an increase in globally averaged temperature during the past century, affects many areas of the world. South America would seem to be one such area, although few accurate measurements have been made.

Even without data from weather stations,

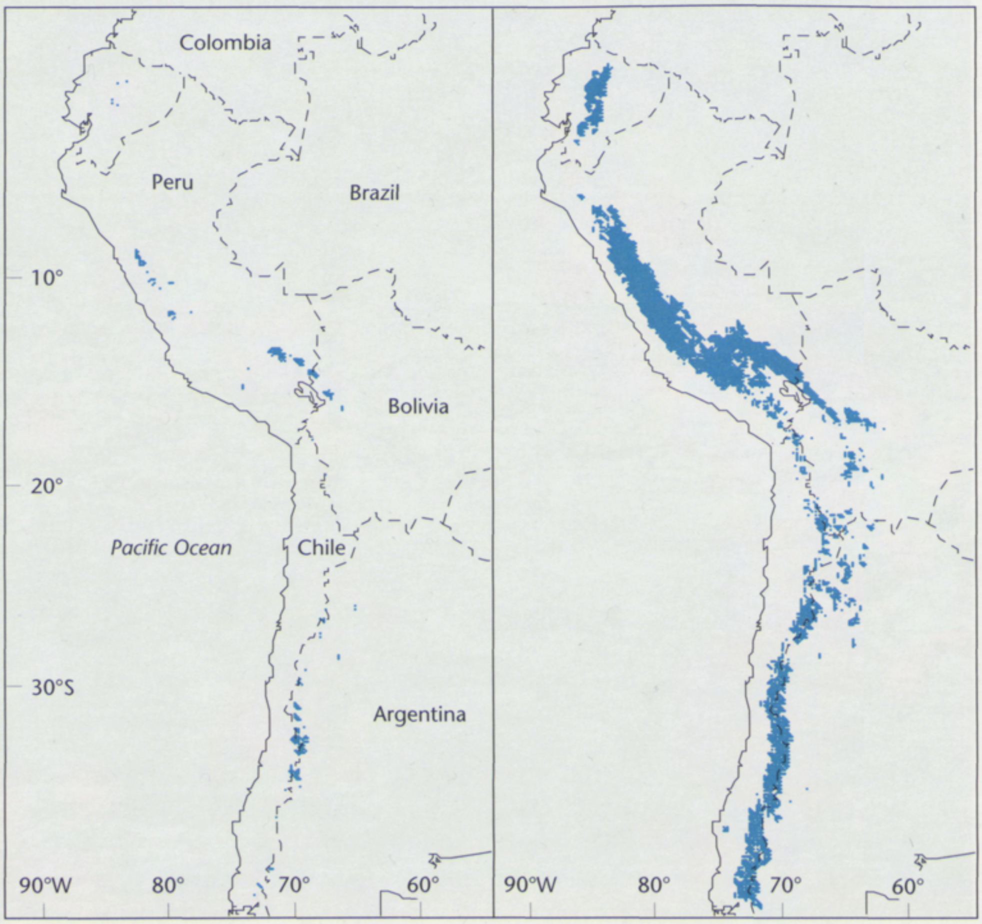


Figure 2. Snowlines in the central Andes. Blue areas show perennial snow cover at present (left), and during the last glacial maximum (right). (Map developed by Andrew Fox)

The interaction of atmospheric and tectonic processes produce soil, which supports life.

the distribution of snow and ice can provide a sensitive measure of mountain climate. Study of this distribution in time and space can provide important new information about regional climate as well as the hydrological and erosional regime. Graduate student Andrew Klein and I are using Cornell's large collection of satellite images to map the elevation and spatial pattern of modern snow lines throughout the Andes. Klein has developed methods to analyze the digital data that produce a semiautomatic determination of snow lines; this can be refined by eye, but the bulk of the work is done by computer. The technique gives a rapid determination of snow line, and these data are then integrated with topographic data to determine snow-line elevation and the relationship of the snow line to other topographic characteristics, such as exposure to solar radiation.

Key to this type of study is the acquisition of images for enough different times so that seasonal and long-term variability in the snow line can be determined. We have such "multitemporal" data for several areas of the Bolivian Andes, and they show clear evidence of a diminution of the snow-covered area over a ten-year period from the mid-1970s to the mid-1980s. Access to more multitemporal satellite data will make it possible to monitor such changes on a global scale in decades to come.

Keeping Track of Large-Scale Processes in the Future

Questions about the interplay between mountain ranges and climate can only be researched because of our ability to deal with these phenomena on an appropriate scale. Huge, remote, mountainous regions that span several different countries could not be studied effectively without satellite imagery and computer graphics techniques that can process and display large amounts of spatial data. Computer systems with sufficient capacity only became economically viable for academic researchers during the past decade, and opportunities to continue this work in the future look especially bright.

In 1988 NASA initiated an ambitious program of earth-observing satellites (EOS) intended to monitor the various components of the global system in a comprehensive way, well into the next century. The Andes Project successfully competed to become one of thirty "interdisciplinary science teams" involved with the EOS project, with a research program focused on erosion as the key component of the interaction between atmosphere and mountains. Other EOS teams cut a similarly wide swath across the disciplinary boundaries of atmospheric sciences, oceanography, ecology, hydrology, and geology.

While the first EOS satellite will not fly

"EOS investigators also have access to new and exciting satellite data from European and Japanese programs"

Bryan L. Isacks is the William and Katherine Snee Professor of Geological Sciences, director of the Institute for the Study of the Continents (INSTOC), and coordinator of the Andes Project. He was educated at Columbia University and after receiving his doctorate in 1965, he conducted research at the Lamont-Doherty Geological Observatory. He came to Cornell in 1971. His research focuses on the way mountains are built. He is a fellow of the American Geophysical Union and the Geological Society of America.

until 1998, a growing research effort with available satellite data is already underway. Arthur Bloom and I are members of a Shuttle Imaging Radar team that will record parts of the Andes and Himalayas in late 1993, and I am principal investigator for a project, sponsored by the Defense Advanced Research Projects Agency, which will develop advanced geographic-information-system techniques and spatial data sets for Asia, Europe, and the Middle East. EOS investigators also have access to new and exciting satellite data from European and Japanese programs, and to rapidly growing national archives developed specifically to study global systems.

THE CORNELL ANDES PROJECT

An Interdisciplinary Study of Mountain Building

The Andes are one of the most spectacular mountain ranges on earth, with the highest peaks in the western hemisphere—or, for that matter, in the southern hemisphere. The Andes are produced by a relatively simple geologic process: the subduction of the Nazca Plate beneath the South American continent. The Nazca Plate, which underlies a part of the Pacific Ocean, is moving to the east-northeast at a rate of about 10 centimeters per year. The force of its collision with the Americas Plate has spawned the largest earthquake on record (8.0 on the Richter scale, in Chile in 1960) and the highest active volcanoes on earth (Ojos del Salada and Llullaillaco, more than 6,800 meters above sea level).

The construction of mountain belts like the Andes is a first-order process in the production and modification of continental crust, which covers about 30 percent of the earth's surface. Such mountain belts are of considerable economic importance because they are the source of much of the world's hydrocarbon and mineral resources. The Cornell Andes Project seeks to understand the formation and evolution of the Andes because they are typical of mountain belts that form along convergent plate margins, and what is learned here can be extrapolated to older mountain belts, such as those in the western United States, where orogenic processes are no longer active.

A Confederation of Individualists

The Cornell Andes Project began in the 1970s, when Cornell geophysicists led by Bryan Isacks and Muawia Barazangi used earthquake data to define the shape of the subducting plate. Realizing the importance of first-order geological variations in South America, they began recruiting other geologists in the early 1980s. One of the strengths of the Department of Geological Sciences is the complete integration of geological and geophysical research, and faculty members with a variety of specialties joined the project. Current members are Richard W. Allmendinger, Arthur L. Bloom, Bryan L. Isacks, Teresa E. Jordan, and Suzanne Mahlburg Kay. Assisting them are three research associates, eleven graduate students, and several undergraduates, who participate in fieldwork as well as laboratory studies and computer work at Cornell. Since its inception, the project has generated thirteen doctoral dissertations (with five more to be defended as this magazine goes to press), well over one hundred publications, and several million dollars worth of sponsored research.

Organization is still informal, however. Large projects are usually supported by a single large grant and structured hierarchically, with a principal investigator and expanding tiers of secondary investigators, post-doctoral associates, and graduate and undergraduate students. In contrast, the Cornell Andes Project is organized as a federation of separately funded, smaller projects whose members trade ideas and information in free-wheeling weekly seminars. Participating faculty members are responsible for generating their own research ideas, procuring their own funding, supporting their own graduate students, and writing their own papers. This egalitarian structure, in which "big science" is conducted as "small science," fosters a competitiveness and enthusiasm that challenges authority and stimulates creativity.

International Collaboration and Industrial Support

Another key factor in the success of the project is close collaboration with colleagues in Argentina, Chile, and Bolivia. Geologists from academia, government agencies, and state-run petroleum companies are involved in most aspects of the work. They participate in fieldwork and coauthor articles, and many have visited Cornell. Reciprocally, faculty members from Cornell have spent sabbatical leaves and

"The construction of mountain belts like the Andes is a first-order process in the production and modification of continental crust. . . ."

taught courses in Argentina and Chile. Graduate students who wish to participate in the project are required to learn Spanish before beginning fieldwork.

Industrial support is also an essential ingredient in the Andes project's formula for success. Exploration for hydrocarbon and mineral resources by international oil and mining companies is at an all-time high in South America, and commercial ventures can make good use of the experience and expertise of the Cornell Andes Project. Reciprocally, collaborating institutions provide travel support for South American colleagues and funding for equipment and digital-database development, as well as access to data that has already been gathered. For example, cooperative agreements with both Argentine and Bolivian state-owned oil companies provide high-quality seismic reflection data that would otherwise be prohibitively expensive. In addition, the oppor-

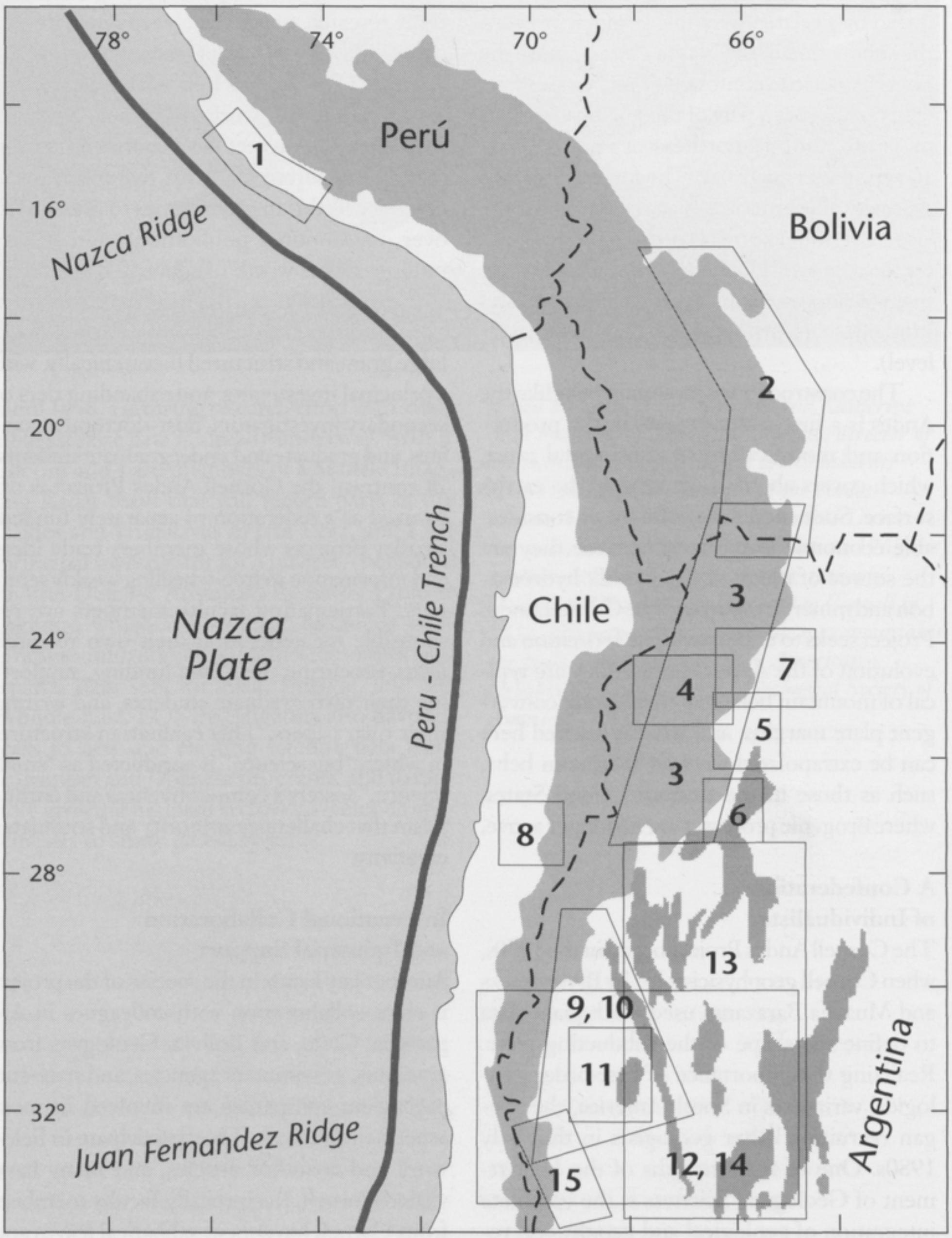


Figure 1. Individual projects conducted under the Cornell Andes Project and their principal investigators. 1. Uplift of Peruvian Coastal Terraces over the Nazca Ridge (A. L. Bloom). 2. High Level Erosion Surfaces in the Bolivian Eastern Cordillera (B. L. Isacks). 3. Late Cenozoic Volcanism and Evolution of the Argentine Puna (R. W. Allmendinger and S. M. Kay). 4. Sedimentary Basin Evolution in an Uplifting Plateau, Argentine Puna (T. E. Jordan). 5. Andean Reactivation of Late Cretaceous Rift Basin Structures (R. W. Allmendinger). 6. Tectonic Geomorphology of the Northern Sierras Pampeanas (A. L. Bloom). 7. Jujuy Earthquake Seismology Experiment (B. L. Isacks). 8. Core Complexes and Mesozoic Rift Basins of Northern Chile (R. W. Allmendinger). 9. Foreland Basin Evolution between the Precordillera Thrust Belt and Sierras Pampeanas Uplifts (T. E. Jordan). 10. Structural Evolution of the Precordillera Thrust Belt and Iglesia Piggyback Basin (R. W. Allmendinger). 11. San Juan Earthquake Seismology Experiment (B. L. Isacks). 12. Evolution of the Andean Magmatic Arc over the Flat Segment of the Subducted Nazca Plate (S. M. Kay). 13. Uplift History of the Sierras Pampeanas Basement Uplifts (T. E. Jordan). 14. Late Paleozoic to Triassic (Gondwana) Silicic Magmatism in Central Chile and Argentina (28°–22°S) (S. M. Kay). 15. Magmatism and Tectonics of Triassic Basins in Western Argentina (S. M. Kay). Two additional projects not located on this map are Magmatic Evolution of the Somuncura Plateau in Northern Patagonia (Rio Negro and Chubut) (S. M. Kay), and The Relation of Miocene to Recent Southern Patagonian Plateau Magmatism to the Collision of the Chile Rise (Santa Cruz) (S. M. Kay).

Working with the Cornell Andes Project, undergraduate Jeffrey M. Abbruzzi participated in a study of seven-million-year-old volcanic rocks in the Andean Precordillera of San Juan province, Argentina.

tunity to interact with scientists in industry gives graduate students perspectives and contacts that can be helpful in their search for employment.

Vast Amounts of Data to Study a Vast Region

Many of the questions that interest members of the Andes project involve large-scale processes that affect huge areas. Research initiatives often require a large body of information and the ability to manipulate it effectively. Thus, spatially extensive databases and an extensive library of literature and maps are crucial to the success of the project. Particularly important is the earthquake database used by the project's geophysicists to continuously improve their model of the subducting slab and to understand processes deep in the crust and the mantle. Members of the project have also created the best digital elevation model available for the central Andes. Furthermore, the distribution of geological features can be displayed relative to the subducting slab and the topography in a quantitatively precise way, using the Cornell collection of Thematic Mapper digital satellite imagery. Also available are spatially extensive data sets for gravity measurements, geochemical analysis of volcanic rocks, and radiometric determinations of the age of rock units.

The Andes project also benefits from sharing ideas and resources with other large Cornell programs. The Consortium for Continental Reflection Profiling (COCORP) provides access to some of the world's most experienced interpreters of seismic reflections. The Cornell Program for the Study of the Continents (COPSTOC) provides a preestablished industrial affiliates program that is ready and able to coordinate relations with industrial partners. And all the faculty members in the Andes project also constitute a team in the Earth Observing Satellite (EOS) program, which is sponsored by the National Aeronautics and Space Administration (see previous article).

All together, the disparate ingredients in the Cornell Andes Project add up to an extraordinarily powerful research capability. Not long ago, the Andes were one of the least-known parts of the earth, and they are rapidly becoming geology's clearest example of orogeny through the subduction of an oceanic plate. In many ways, the Andes project is a model of how such productive, wide-ranging research can be carried out.

DEEP SEISMIC EXPLORATION IN TIBET

by Larry D. Brown

"Because such buried features are hidden from direct observation, geophysical techniques must be used to map them."

More than two-and-one-half miles high, the village of Gala is situated on the ancient trade route from India to Lhasa, the once-forbidden capital of Tibet. Now isolated and hard to reach, Gala is normally off-limits to non-Chinese visitors. But last summer the village served as a base camp for a major new geoscience project intended to probe the roots of the Himalayan mountain belt. A cooperative effort of geologists from China and the United States, the project has been dubbed INDEPTH, for INternational DEep Profiling of Tibet and the Himalaya. The survey undertaken in the summer of 1992 was an inaugural test of a proposed 1,200-mile seismic transect across the entire Himalayan-Tibetan Plateau. This is a vast area of extreme elevation raised by the collision of the Indian subcontinent with the underbelly of Asia, which started some twenty million years ago.

For years the Himalaya Mountains and Tibetan Plateau have stood as a kind of Rosetta Stone for geophysicists, the type case for crustal accretion by the collision and suturing of continents to form a larger continental mass. Over the past decade, Chinese and Western geologists have focused increasing attention on this region. Some have sought to understand the relationships between structures and rock units at the surface, while others have contemplated the possible mechanisms by which the Indian continent has been thrust northward, under the Asian continent.

One school of thought envisions the uplift of the Tibetan Plateau as a simple result of the compression of the Asian continent by the force of the collision. Another view argues that the plateau is a result of underthrusting by the buoyant Indian continent, which has pushed deep under the Asian interior. Even more complex theories take into account the results of a seismic experiment performed by a Chinese-French collaboration in the early 1980s, which suggest that the base of the underthrust Indian continent is imbricated—offset by major faults.

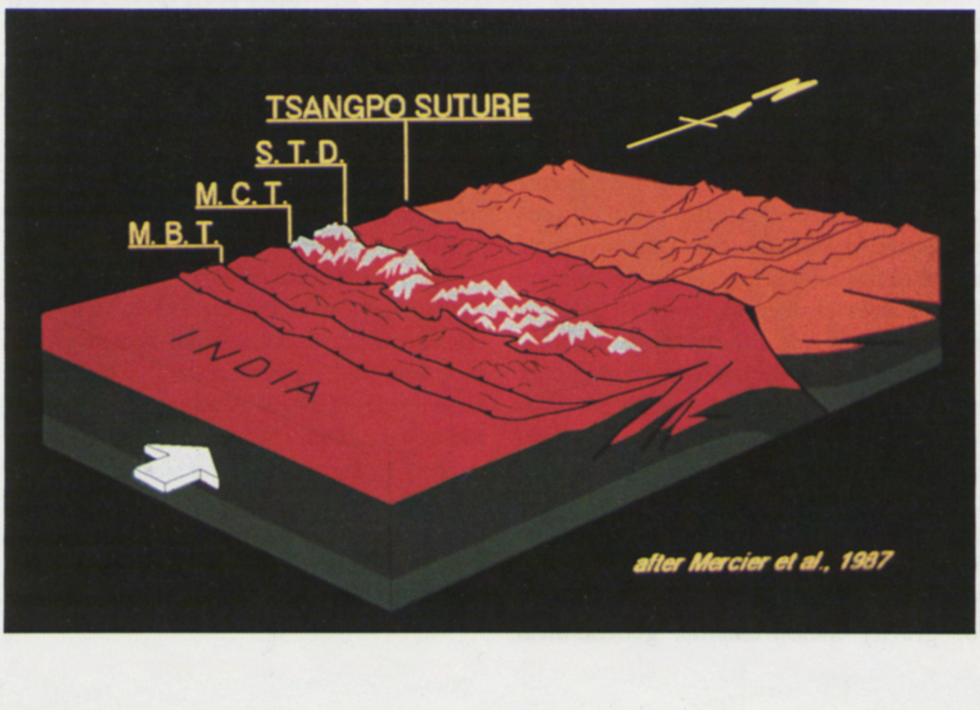


Figure 1. Hypothesized structure of the Himalaya Mountains and the Tibetan Plateau. This is one of several models that Project INDEPTH was designed to test.

High Himalayas tower over Dogen Valley, site of Project INDEPTH's pilot survey. Mt. Chomolhari, on the right, attains a height of 24,000 feet.

On one point all interpretations agree. The crust beneath Tibet is unusually thick—up to twice the thickness of the continental crust found in most other places. The geometry of thrust faults, the penetration of India beneath Asia, and the location of the Moho (the seismic discontinuity showing where crust meets mantle) are important clues to the evolution of this key region. Because such buried features are hidden from direct observation, geophysical techniques must be used to map them.

An International Project in Deep Seismic Reflection Profiling

Western scientists have had access to this key region only since the 1970s, and only on a limited basis. But during this period, China was slowly becoming receptive to the possibility of collaboration with Western geologists.

At the same time, a powerful geophysical technique for the subsurface exploration of continental crust was gaining in prominence. Seismic reflection profiling uses sound waves generated at the surface and reflected back from deep underground to map buried rock interfaces. The technique was developed by the petroleum industry, but the Consortium for Continental Reflection Profiling (COCORP), based at Cornell, undertook to exploit its potential for studying the deeper structure of the earth's crust. The technique proved so successful that it was soon being used in many parts of the world.

While deep seismic profiling solved some geological problems, it uncovered others. A good example is the strikingly laminated character of the lower crust beneath many continental areas. Is this evidence for ductile deformation of preexisting rock fabrics, or does it result from the intrusion of molten material from the underlying mantle? Why is the base of the crust (the Moho) apparently flat beneath many areas, even where the crust is known to have undergone complex deformations, while it appears to be faulted and thrust into the underlying mantle in other areas?

To help answer such questions, data are needed from geological terranes that represent key stages in continental evolution. As the world's best example of active collision between two continents, the Himalaya–Tibetan Plateau is crucial. Yet its remote location, complex terrain, and international character constitute daunting challenges to mounting a systematic seismic survey. Moreover, getting vibrations to penetrate Tibet's double-thick crust all the way down to its base requires extraordinary measures.

Geologists in both China and the United States recognized the need to probe the deep structure of Tibet, but mounting an expedition that could actually collect seismic data was

Members of the Chinese seismic crew observe an explosion. Water spouts were caused by 50-kilogram charges of dynamite, which were set off in boreholes. A drilling rig can be seen in the background.

a long, complex process. A decade of negotiations finally led to plans for a test survey, to be carried out by a partnership between China's Ministry of Geology and Mineral Resources (MGMR) and the Geodynamics Program of the U.S. National Science Foundation. The work would be done by a Chinese seismic crew, under the direction of a binational team of scientists including Douglas Nelson (associate professor of geology at Syracuse University and adjunct associate professor at Cornell), John Kuo (professor emeritus at Columbia University), Professor Zhao Wenjin of the MGMR, and myself.

Shaking the Mountains Down to Their Roots

The INDEPTH project was conceived as a pilot survey that would explore a line approximately 100 kilometers long in the center of the Himalaya thrust belt. The whole enterprise was fraught with difficulties. The MGMR had been carrying out seismic surveys for petroleum exploration in the Tibetan Plateau, but no one had attempted a seismic survey in the central Himalayas. Elaborate equipment and a large crew of Chinese explorationists had to be transferred and supported in this remote location. There was concern that some of the computing equipment, necessary to monitor the data collection, might not even work at an altitude in excess of 8,000 feet. In order to study extremely deep targets such as the Moho, seismic waves would have to be produced with explosives. Deep shot holes, drilled in highly variable surface rocks, would be necessary in order to assure that enough energy was sent into the ground. And in addition to everything else, there were the problems of coordinating activities among more than two hundred individuals, compounded by the fact that the project's directors spoke different languages and came from different scientific cultures.

The core profile was collected using a 120-channel seismic recording system with receivers (geophone groups) spaced 50 meters apart. Ideally, the seismic vibrations would be produced with 50 kilograms of dynamite placed in holes 50 meters deep and spaced 200 meters apart. But drilling to the full 50 meters was frequently impossible because of the geologic conditions. To compensate for this, an extra-large shot, using 200 kilograms of dynamite, was recorded every 6 kilometers. The weather also caused problems. Rain showers were frequent, wetting the equipment and causing electrical noise. The wind was erratic, and often picked up just as recording was about to begin—which added to the noise. Efforts were made to minimize this noise, but they were not always successful.

To maximize the information recorded during the experiment, auxiliary seismic instruments were deployed at stationary sites along the primary reflection survey routes, as well as off to the sides and at the ends. These instruments were intended to improve the measurement of subsurface rock velocities, which are an important parameter both for processing the main reflection data and for constraining subsequent identification of buried features. The lateral receivers also helped define three-dimensional aspects of reflector geometry. This auxiliary recording experiment was designed and executed by Simon Klemperer, who worked with COCORP while a graduate student at Cornell, together with his students at Stanford University, Yitzhaq Makovsky and Hal Mendoza.

The ability to process recorded data in the field, rather than wait for it to be shipped back to Beijing or Cornell, was critical to the success of the project. A DEC workstation equipped with a new interactive seismic-processing software package known as ProMAX was configured, shipped, and operated under adverse conditions by Michael Hauck, a Cornell graduate student.

Hauck and Makovsky were the only members of the U.S. field team to stay for the entire experiment, from beginning to end. They developed a special rapport with the Chinese seismic crew and the Tibetan villagers, although they never learned to appreciate yak stew and butter tea. Food aside, no one who participated in this research will ever forget the hospitality of the Tibetan people. Although few, if any, had any idea of what we were about, they were unfailingly friendly and helpful.

Preliminary Results and Future Plans

The seismic data collected during Project INDEPTH are still being analyzed. A group of Chinese scientists led by Professor Che Jingkai visited Cornell in March to compare results and analyses. It is already clear that the survey was a major success. Distinctive reflections from depths of 30 to 40 kilometers show what is almost certainly the main fault along which the Indian continent is sliding under the Himalayas. On a portion of the line, even more prominent reflections show up from a depth of 75 kilometers, the

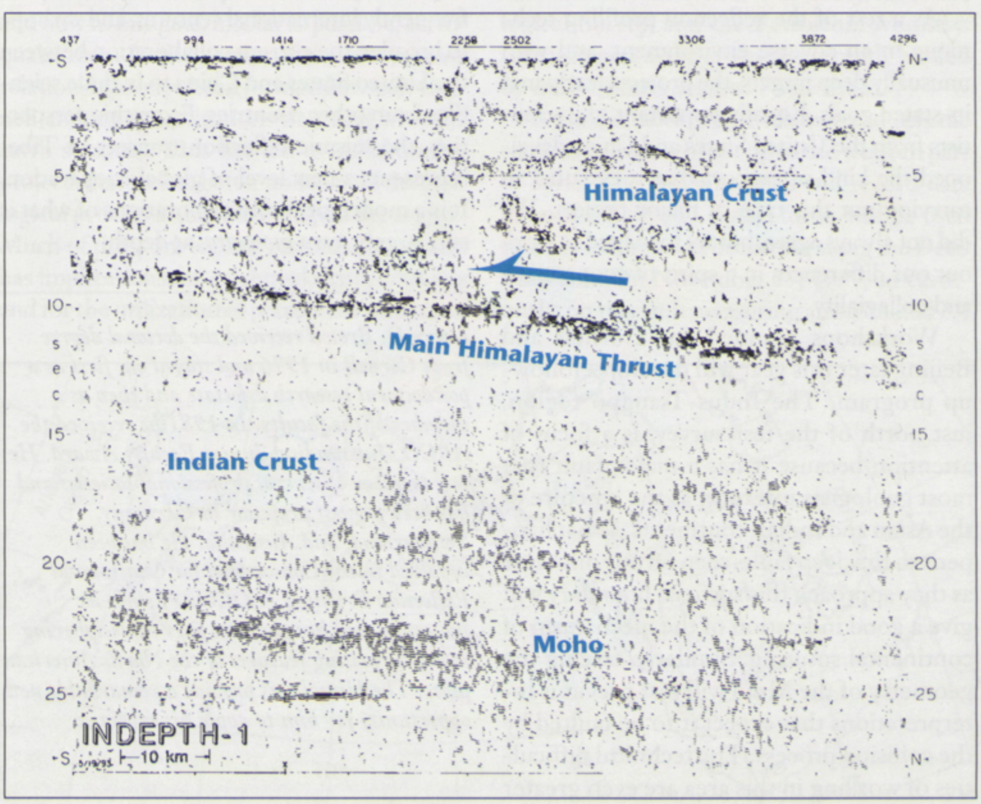


Figure 2. Initial results from Project INDEPTH. This acoustic "echogram" shows features deep in the earth. The strong reflections slightly above the middle are interpreted as the main Himalayan thrust fault, some 30 to 40 kilometers below the surface. Above this fault are complex structures that have formed the Himalayas; below it the Indian crust is sliding beneath Asia. The strong reflections near the bottom of the section are thought to be from the Indian Moho, or crust-mantle boundary. This is the deepest Moho ever seen by reflection profiling.

U.S. scientists enjoy a break in the field "computer center." Pictured, from left to right, are Simon Klemperer (Stanford University), Hal Mendoza (Stanford graduate student), Larry Brown (Cornell University), Michael Hauck (Cornell graduate student), and Douglas Nelson (Syracuse University and Cornell). The computer room and living quarters were in a local police station; the officers were warm and enthusiastic hosts.

predicted location of the Moho. Other reflections mark additional complexity within the crust. Some of these features may be related to earthquakes in the Himalayan region, a possibility now being investigated by Cornell graduate student Douglas Alsdorf.

As a test of the reflection profiling technique in an adverse environment, and with unusually deep targets, the project clearly met its stated goals. Equally important, the scientists from the United States and China developed the kind of rapport that is essential to carrying out this type of major project. We did not always agree, but we managed to work out our differences in a spirit of cooperation and collegiality.

Workshops planned for Cornell and Beijing later this year will develop a follow-up program. The Indus-Tsangpo region, just north of the test survey, is a focus of attention because it has a major fault that most geologists interpret as the juncture of the Asian and Indian continents. What happens to the deep faults seen on our pilot line as they approach this surficial boundary will give a good indication of the mechanism of continental suturing. Similarly, tracing the geometry of the Mojo will test previous interpretations that expect it to be faulted by the collision process. The technical difficulties of working in this area are even greater than those encountered in the pilot survey, but the experience we have gained makes us confident that we will be able to overcome them.

Projects of the scope of INDEPTH are an important part of solid earth science. They are frequently international ventures, and we hope to broaden the current collaboration between the United States and China to include scientists from other countries. From this perspective, the seismic reflection transect of Tibet represents a new level of global cooperation. It is a model for future explorations of what is still largely *terra incognita*, at depth.

Larry D. Brown received the doctoral degree from Cornell in 1976 and stayed on, first as a postdoctoral research associate and then as a member of the faculty. In 1981 he received the ARCO Outstanding Junior Faculty Award. He is a member of several professional societies and has been a guest professor in Germany, Switzerland, and Australia. He has been involved in the Consortium for Continental Reflection Profiling (COCORP) since its inception, and has played a part in deciphering many surprising features of the North American plate. The Himalayas provide a remarkable new opportunity for him to apply his expertise.

EARTHQUAKES AND OIL

Collaborative Research in the Arab World

by Muawia Barazangi

The complexity of tectonic processes in North Africa and the Middle East is only surpassed by the complexity of the region's politics. Three destructive earthquakes in the early 1980s (in Algeria, Egypt, and Yemen) catalyzed an initiative to better understand these processes. The Programme for Assessment and Mitigation of Earthquake Risk in the Arab Region (PAMERAR) was set up by the United Nations Educational, Scientific, and Cultural Organization (UNESCO) to provide a comprehensive plan for assessing and addressing earthquake hazards. I was one of nine scientists selected by UNESCO to carry out the study.

So far, PAMERAR has been active in Algeria, Jordan, Morocco, Syria, Tunisia, and Yemen. It has provided detailed guidelines on how to initiate and implement a comprehensive program of earthquake-hazard assessment and how to mitigate, insofar as possible, earthquake risks. In the course of this work, close relationships have been formed between Cornell and many institutions that deal with the earth sciences. This has led to collaborative projects that seek to better understand the geological processes that have shaped the region. Much of the work is basic research, but it also has implications for earthquake preparedness and for the utilization of petroleum resources.

Setting up Seismic Networks

A National Seismic Network of twenty-five stations has recently been established in Morocco. Data recorded by this telemetered digital network, as well as other data (including digital topography and gravity measurements, seismic reflection and refraction profiles, and Landsat imagery), will all contribute to the assessment of earthquake hazards. They will also make possible a better understanding of the crustal and upper-mantle structure of the intraplate Atlas Mountain belt, which is fundamentally different from most mountain belts located along convergent plate boundaries, such as the Himalayas and the Andes. The project was set up as a cooperative venture involving Cornell and the Morocco National Research Center, in Rabat, as well as the Scientific Institute of Mohammed V University, the Geological Survey, and the Petroleum Ministry. Cornell's part in the project is currently funded by the National Science Foundation.

A similar network of telemetered seismic stations will soon be set up in the western part of Syria. The system, which will record data in both analog and digital form, will be used to study earthquakes occurring along the Dead Sea Fault. On November 25, 1759, an earthquake on this fault measuring an estimated 7.4

"Much of the work is basic research, but it also has implications for earthquake preparedness and for the utilization of petroleum resources."

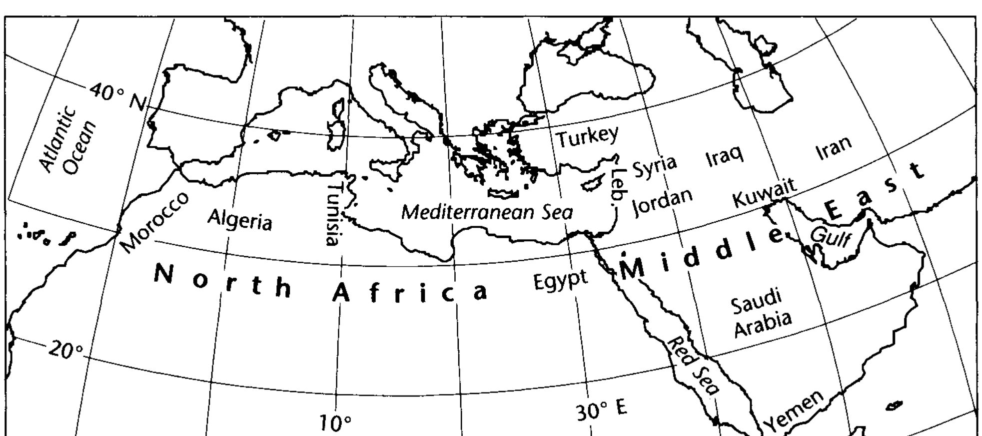
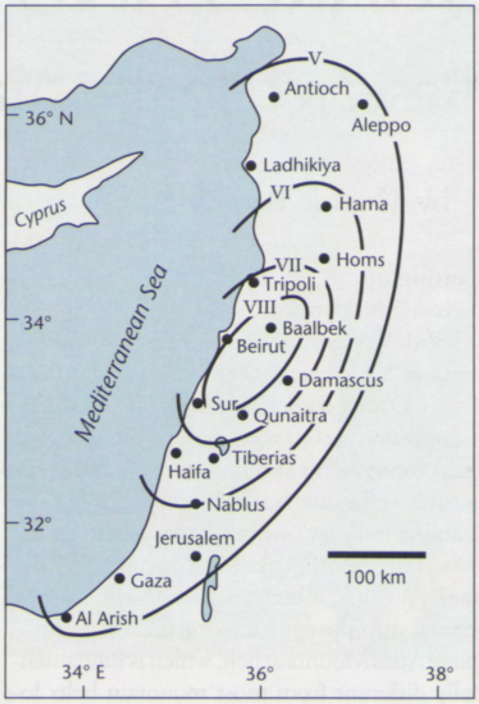


Figure 1. North Africa and the Middle East. Contacts are maintained between Cornell and earth scientists in all the countries labeled.

Figure 2. The earthquake of November 25, 1759. The epicenter and intensity distribution have been worked out from historical documents.



on the Richter scale devastated Damascus, Aleppo, and Beirut, among other cities, causing great loss of life. The relative absence of large earthquakes along the Dead Sea Fault during the past century should not be taken as an indication that activity has ceased, and similar disasters could occur at any time. The seismic network is the first step in implementing PAMERAR in Syria, and will be supervised by the General Establishment for Geology and Mineral Resources. Cornell will sign a contract with UNESCO to participate in the project and train the Syrian scientific and technical staff.

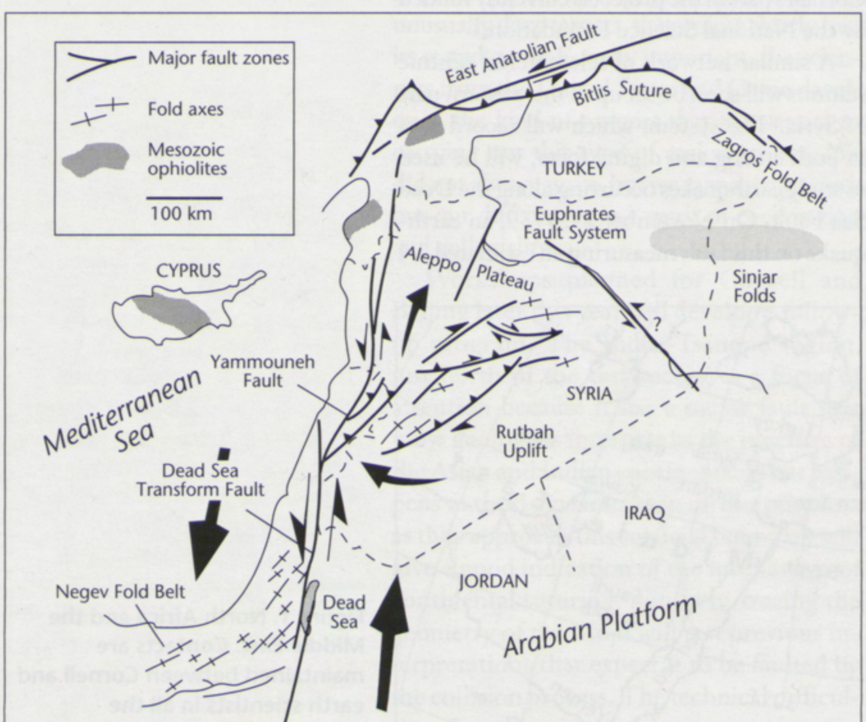
Saudi Arabia established a modern seismological observatory, with the help of Cornell personnel, at King Fahd University of Petroleum and Minerals in Dhahran. Kuwait is also planning an observatory, in recognition of its proximity to the Zagros earthquake belt in nearby Iran and Iraq. But this initiative, which would also involve input from Cornell, was interrupted by the Gulf War.

Cooperative Projects with Available Data

For the past five years Cornell geologists and geophysicists have been conducting a comprehensive study of the geologic history, evolution, lithospheric structure, and active tectonics of Syria. This is a cooperative venture among Cornell, the Syrian Petroleum Company (SPC), and a number of international oil companies (Amoco, Arco, British Gas, Exxon, Marathon, Mobil, Occidental, and Unocal). SPC is providing all the required data, which currently include over 12,000 kilometers of seismic reflection lines, tens of well logs, seismic refraction profiles, gravity observations, and other material. Cornell and SPC scientists are providing the expertise to analyze this information, and the oil companies are contributing funds to support the project. There are reciprocal visits between Syrian scientists and Cornell personnel; oil companies have sent representatives to discuss the progress of the project, and two graduate students who earned their doctorates working on the project now work in the petroleum industry.

Recently, the National Petroleum Company of Morocco has agreed to join Cornell in a cooperative study that will reanalyze and reinterpret seismic reflection profiles and well logs. Similar in spirit to the collaboration with the Syrian Petroleum Company, this is a golden opportunity to use data that already exist to achieve a better understanding of crustal structure and evolution. The results

Figure 3. Regional kinematics of the northern Arabian Platform. Arrows show the motion of different structures relative to each other.



Currently working on projects in Morocco and Syria are (clockwise from left): George Hade, research engineer; Dogan Seber, graduate student; Muawia Barazangi, faculty member and project leader; Enid Williams, undergraduate; Robert Litak, postdoctoral associate; and Kathleen Taylor, undergraduate.

Barazangi, who received his doctorate in seismology from the Lamont-Doherty Geological Observatory at Columbia University, is a senior scientist in the Department of Geological Sciences and associate director of the Institute for the Study of the Continents. A native of Syria, he has established contacts with earth scientists throughout the Arabic-speaking world. In 1979 and '80, he was an associate professor and chair of the Department of Geophysics at King Abdulaziz University in Jeddah, Saudi Arabia.

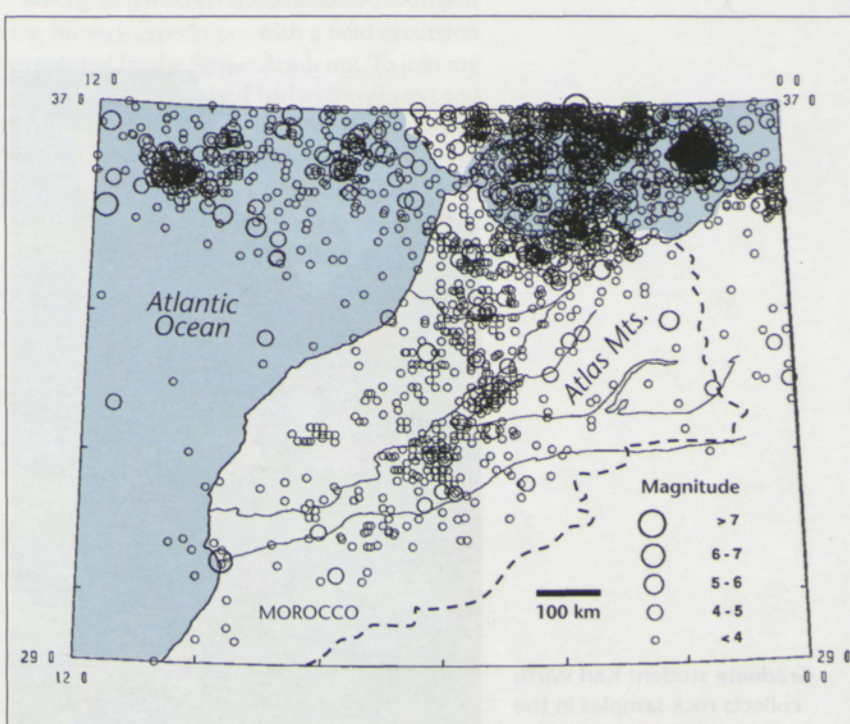
may also make it possible to map active seismogenic faults at depth, contributing to a better evaluation of earthquake hazards.

The work in both Syria and Morocco involves a synthesis of information from many disciplines in the earth sciences, including geophysics, geology, and remote sensing. These disciplines contribute data that become part of a comprehensive interpretation of regional geologic processes. In addition, practical information is made available to those who can use it, without regard for national boundaries. In many ways, the Syria project is a workable, successful model for the international transfer of information and knowledge.

Broadening the Scope of Cooperative Research

In 1986, I was named coordinator of the Global Geoscience Transects (GGT) project for the Middle East and North Africa. A part of the International Lithosphere Program, the GGT uses geological and geophysical data to compile lithospheric cross sections in a standardized and systematic way so that the continental lithosphere in all parts of the world can be directly compared. In the course of my work with the GGT, communications have been opened between Cornell and institutions in several more countries, including Algeria, Egypt, Iran, Iraq, Kuwait, Lebanon, Saudi Arabia, Turkey, and Yemen. All together, geoscientists from about a hundred countries are working in this effort, making it one of the most successful international cooperative projects in the earth sciences.

Figure 4. Earthquakes in Morocco and nearby regions, 1900–89.



GEOLOGICAL FIELDWORK IN THE SPACE AGE

by John M. Bird

"During the past century, engineering advances have dramatically affected geological research."

Has geological fieldwork, with boots, hammers, and strong backs, been replaced by computers and satellites? During the past century, engineering advances have dramatically affected geological research. Railroads, automobiles, and aircraft greatly accelerated the pace of geological exploration. The use of submarines during the Cold War fostered geophysical study of ocean floors—about 70 percent of the earth's solid surface. These studies used electronic sensors that provided information that led to the development of plate tectonics. Lunar rocks brought back by the Apollo astronauts sparked a great effort in analytical geochemistry. The chemical evolution of the solar system is being studied with devices that have sensitivity and precision that were impossible just a few years ago. Major advances in geological research are now possible because of developments of electronic computing and electromagnetic sensors. Satellites containing amazing electronic devices are put into orbit to study the surface and interior of the earth and other planets. Some leaders of the geological sciences have suggested that much of the fieldwork done by geologists during the past century will be redone with computers and satellite technology. However, geologists will continue to do conventional fieldwork, especially in remote and poorly known wilderness regions.

Graduate student Karl Wirth collects rock samples in the Maiyumerak Mountains.

Over the course of eight years, I was principal investigator of two research projects funded by the National Aeronautics and Space Administration that utilized satellite-acquired data to study oceanic rocks tectonically emplaced in mountain belts. These rocks, known as ophiolites, are particularly well-exposed in the Brooks Range of Alaska. The research combined Landsat satellite data and field exploration in this remote wilderness to study the origin and evolution of the Brooks Range ophiolites and their subsequent deformational and erosional history. The work involved a combination of satellite imagery and geochemical analysis of rock samples. Much of the fieldwork was done by my graduate students. Their resulting education and perspective of the science could not have been predicted a decade ago, even by the most prescient advisor.

The First Trips: Making Surveys and Collecting Rock Samples

Our field studies began in the summer of 1985. David Harding, Karl Wirth, and Deborah Shelton as field assistant went to Kotzebue, a small village on the Bering Sea, just north of the Arctic Circle. Exploration geologists of Cominco American Incorporated provided them with plane and helicopter transport to places of interest in the regions of Asik Mountain, Maiyumerak Mountain, and the Avan Hills. Once on the ground, the students had to carry all their gear, as well as the rocks they collected, over miles of tundra. Exposed rocks are mostly found high above river valleys, and

Karl Wirth and his brother Roland prepare to make camp on the Porcupine River.

a major logistical obstacle was finding water, because the climate of the high arctic regions of Alaska is much like a desert.

On a second trip to Alaska, in the summer of 1987, David Harding, Karl Wirth, Ann Blythe, and Jan Romick as field assistant went into the central Brooks Range. A float plane carried them, together with camping gear and two canoes, from Bettles—a small village northwest of Fairbanks—to the headwaters of the Noatak River. This river flows west along the Brooks Range, providing a route through regions of interest to our research. The students were completely on their own for more than a month as they paddled down the river, carrying all their equipment and a growing collection of samples. They hiked many miles away from their campsites on the river to collect rocks and data. Eventually they arrived at Noatak Village, some 150 miles downstream. There, they were able to subcontract helicopters from the U.S. Geological Survey to return to previously visited sites in the western Brooks Range.

One objective of the research was to better understand the history of uplift and erosion in the region. Ann Blythe undertook part of this work by analyzing fission tracks in minerals. Fission tracks are regions of damage of the crystal lattice of a mineral caused by the natural fission of uranium-238. Analysis of fission tracks involves neutron irradiation, polishing, etching, and microscopic study. In general, temperature and depth beneath the earth's surface can be determined from fission tracks, and from that information estimates of timing and rates and amount of uplift and erosion can be worked out.

I was in northeastern Siberia at the time of the Noatak expedition, with a field excursion organized by the Soviet Academy. To join my students in Fairbanks, I had to travel west and almost circumnavigate the globe, rather than make a short trip to the east. Ann Blythe, Karl Wirth, and I then took a trip northward along the Dalton Highway. This road, which is not open to the general public, follows the Alyeska pipeline northward through the Brooks Range into the Colville Basin. It made possible a 150-mile transect, along which we were able to obtain a suite of rocks to begin our fission-track studies. The use of a four-wheel-drive truck allowed us to set up a comfortable camp at the end of each day.

One of the World's Most Remote Regions

Analysis of the satellite images we had prepared and the collected rocks generated an enormous amount of data, and the graduate students' results were now important in determining where to go next when we resumed fieldwork in 1989. Ann Blythe and Jan Romick set out along the Dalton Highway to complete a detailed sampling of rock from the Brooks Range and Colville Basin. Meanwhile, I flew by float plane to the intersection of the Porcupine River and the Canadian border, together with Karl Wirth and his brother Roland, an expert in wilderness survival. We hoped to find some volcanic rocks that we predicted to be in the region on the basis of evidence Karl and I had found in the Yukon Basin. We found some lava flows that turned out to be about three hundred thousand years old and of great significance to our research. Karl and Roland continued exploration on the Black River, while I returned to Coldfoot, about halfway between Fairbanks and Prudhoe Bay, to meet Ann Blythe and Jan Romick. After several weeks of sand, bugs, dried "food," and endless miles of wilderness, it was a great pleasure to join them at a meticulously neat camp, with chairs to sit in, and one of the best suppers I have had in the field.

I rejoined Karl and Roland in Fairbanks, where we reoutfitted and headed to Bettles. There, we experienced a hair-raising liftoff from a flooded river, with several hundred pounds of gear and many cans of aviation fuel strapped to our plane's pontoons. We wanted to examine some rocks, reported by U.S. Geological Survey geologists, that we thought could be ophiolites. We landed on a tiny cirque lake on Siniktanneyak Mountain, set up camp, and explored for several days. The cirque lake was too small for the plane to take off from when fully loaded, so we had to meet the pilot at another lake, some fifteen miles away. Karl and Roland carried packs that I could not lift. On the walk, we watched the largest grizzly bear I have ever seen. Because these bears can be very dangerous, my students had received fire-arms training from Walter Pagliaro, ex-deputy chief of the Ithaca police, and always carried a large-caliber rifle, a shot gun, or a long-barrel .44 magnum pistol in the field.

The next day we rendezvoused with another bush pilot, and I left Karl and Roland and returned to Ithaca. They continued west in a Piper Cub that left them in high mountains, in one of the remotest parts of the Brooks Range. Several weeks later, they were ten days late in reporting back to me from Kotzebue. The weather had changed suddenly and deep snow had fallen. Only the bush pilot knew where they were. When the weather cleared, he managed to land the Piper Cub on the side of a mountain, where he picked them up and took off, fully loaded, downhill, on a snowy and rocky slope. During a week of their isolation, Karl and Roland had nothing to eat but a roasted marmot, and they had shot up all their ammunition to get it.

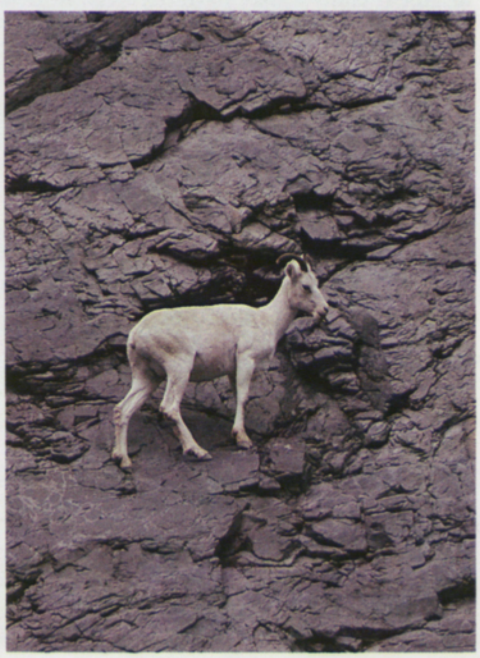
Members of the field party unload their gear from a Cessna on a cirque lake on Siniktanneyak Mountain.

Karl Wirth and Deborah Shelton in the Maiyumerak Mountains.

Scientific Results and Educational Results

The Alaska Project involved several research objectives. The first objective was to prepare satellite images of the regions of suspected ophiolites in the western Brooks Range. This was done by processing digital data from a Landsat satellite, recorded on tape, to produce false-color images of the earth's surface. Harding became expert in this technology. There are several bands, or spectral intervals, of sensed electromagnetic radiation in the Landsat data that are useful for geologic exploration. Using imaging hardware and software, entire quadrants of Thematic Mapper data, measuring 120 kilometers on a side, were examined as computer-generated three-band color composites. By assigning red, green, and blue to appropriate bands, it proved possible to differentiate exposed rock, vegetation, and hydrothermal alteration. When we compared the images with the rocks, we were able to establish the usefulness of satellite data for constructing geologic maps of large, remote regions without having to examine the sites on the ground.

This work made it possible to map large regions of ophiolites in the western Brooks Range. We determined various types of rock within the ophiolites and the general structural configurations of the ophiolite masses. Our maps provided a basis for modeling the origin and evolution of the ophiolites. Using argon-argon isotope data and trace-element geochemical analyses, we reconstructed the mechanisms by which the Brooks Range ophiolites were driven out of the Pacific Ocean approximately 180 million years ago. The resulting uplifted Brooks Range provided sediment that was deposited in the Colville Basin



High in the Brooks Range, Dall's sheep show little fear of people.

The author on Jumbo Dome, south of Denali.

to the north. Ann Blythe's study of fission tracks showed that erosion rates in the Brooks Range approximately sixty million years ago were much greater than either before or since. The relations between uplift and erosion of an evolving mountain belt are complex, and may be related to changes in global climate (see article by Isacks, this issue). Independent data from deep-sea sediments in the southern Pacific Ocean indicate that a significant change in global climate may have occurred at that time.

What made our Alaska research successful was the energy and enthusiasm of the students. The students left the high-tech world of Cornell laboratories and entered a world that requires self-sufficiency and back-breaking effort. In the remote wilderness, they lived in isolation, among wolves and bears, and their views of life and the world were forever changed. They helped each other and they became motivated to think and work on their own. They became inventive and eventually they completed innovative theses.

David Harding is now a research scientist at the Goddard Space Flight Center in Maryland. He has become an expert in remote sensing and the interpretation of satellite images. He has recently studied geologic features of the Ethiopian rift valley by this technology. Karl Wirth is assistant professor of geology at Macalester College in Minnesota. His research concentrated on the geochemistry of the Brooks Range ophiolites; he and I are continuing studies of volcanic rocks from the Brooks Range. Ann Blythe is assistant professor of geology at Whittier College in California. She is continuing fission-track studies with colleagues at the University of California at Santa Barbara.

John M. Bird, who is widely known for his work with ophiolites and plate tectonics, joined the Department of Geological Sciences in 1972. Previously, he received the doctorate from Rensselaer Polytechnic Institute (1962), taught at the State University of New York at Albany, and served as a senior research associate at Lamont-Doherty Geological Observatory. He has been a distinguished visiting scientist of the American Geological Institute and a distinguished visiting lecturer of the American Association of Petroleum Geologists. He is a fellow of the Geological Society of America, the Geological Society of Canada, and the Explorers' Club.

NEW MEETING GROUNDS

Collaborative Research in the Urals and Kamchatka

The dramatic social and political changes that have transformed the former Soviet Union over the past few years have paved the way for exciting new initiatives in geological exploration. During the Cold War, a vast portion of the Eurasian land mass, stretching across thirteen time zones, was largely off limits to scientists from the West. Now, after the institution of a policy of *glasnost* and the breakup of the Soviet Union into separate republics, scientists from East and West are beginning to collaborate on a variety of projects. The Institute for the Study of the Continents (INSTOC) and the Department of Geological Sciences at Cornell have been taking advantage of these opportunities, developing a broad program of geological research in the former Soviet Union.

A major study of the Urals, led by research associate James H. Knapp, is being undertaken in collaboration with scientists from both the Russian Ministry of Geology and the Russian Academy of Sciences. A 3,000-kilometer-long orogenic belt of Paleozoic age, the Urals offer an excellent opportunity to study mountain building and the evolution of continental crust. Scientists from the Bazhenov Geophysical Expedition (in Scheelite) are sharing an extensive geophysical database that includes deep-seismic sounding, reflection, gravity, magnetic, and heat-flow data for the Urals. The long-term objective, however, is to collect a deep seismic reflection profile across the range. There are many similarities between the Urals and the Appalachians, and a multidisciplinary team of experts from the United States and Russia will study their comparative anatomy.

The actual work of profiling in the Urals will be carried out in conjunction with EUROPROBE, a major new initiative dedicated to the study of tectonic evolution throughout Europe. One focus of EUROPROBE's work is a comparative study of the Urals and the Variscan Orogenic Belt of Europe. This multidisciplinary collaboration of INSTOC personnel with numerous Russian and European

"scientists from East and West are beginning to collaborate on a variety of projects."

Zolotaya Gora, in the serpentinites of the main Uralian fault, is the site of one of Russia's most productive gold mines.

scientists marks a new level of international cooperation in deep seismic reflection profiling.

Far away, at the other end of Russia, the political thaw has greatly facilitated the study of continental growth along the Pacific margin. There, the inexorable drift of the lithosphere under the northern rim of the Pacific Ocean is slowly carrying fragments of Russian America (the Aleutian Islands) westward toward Russia itself (the Kamchatka Peninsula). For several years, Robert Kay and Suzanne Mahlburg Kay have conducted fieldwork in the Aleutians, in an effort to define the process of continental growth and assembly. The farthest west they could go was Attu, the last island belonging to the United States, where they studied pillow lavas and plutons that had formed beneath the sea. But the ultimate fate of Attu will be fusion with the Kamchatka mainland, and the logical next step was to study fragments that had already "docked."

Political considerations interfered, however, until 1989, when then–graduate student Gene Yogodzinski served as a staff scientist on the Russian research ship *Volcanolog*. Subsequently, Oleg Volynets, from the Institute of Volcanic Geology and Geochemistry in Petropavlovsk, Kamchatka, visited Cornell for three months and Yogodzinski initiated field investigations in Kamchatka. Further collaborative studies are planned.

Above: One of the many volcanoes of the Kamchatka Peninsula, where fragments of the Aleutian Island Arc are docking with the Russian mainland.

Right: Cornell graduate student Gene Yogodzinski (left) and Ivan Milikesev (right) were given a lift by an unidentified Aeroflot pilot. Milikesev is a geologist with the Institute of Volcanic Geology and Geochemistry in Petropavlovsk.

NEW FRONTIERS CLOSE TO HOME

North America's Central Corridor

by Lawrence M. Cathles III and Ernest C. Hauser

Between the Rocky Mountains and the Appalachians is a huge, flat area known to geologists as North America's Central Corridor. At first glance it would appear to be tectonically inactive and geologically uninteresting. Yet lying below a relatively thin and relatively undisturbed cover of sedimentary rocks is a complex mosaic of deeply eroded ancient mountain chains, incipient oceans that failed to open, and buried sedimentary basins. Since the Central Corridor was not deformed into dramatic topography and exposed by erosion, as were the Rockies and the Appalachians, evidence of processes that produced these buried features has been well preserved, although it must be read mainly from deep-seismic-reflection sections analyzed and interpreted through computer-processing and -modeling techniques. The stable Central Corridor is also an ideal place to observe and investigate ongoing processes, such as the regional flow of groundwater and the migration and trapping of hydrocarbons.

Roots of Mountains and Continental Rifts: Mysterious Features from the Precambrian

For several years the Consortium for Continental Reflection Profiling (COCORP), based at Cornell, has been running deep-seismic-reflection transects that show cross-sections of the continental crust under the United States. A similar effort, called LITHOPROBE, has been active in Canada. One of the surprising features recently revealed by this work is the deep structure of the Trans-Hudson Orogen—the eroded roots of an ancient mountain belt. This belt consists of deformed basement rocks that are exposed

"lying below a relatively thin . . . cover of sedimentary rocks is a complex mosaic of . . . ancient mountain chains, incipient oceans that failed to open, and buried sedimentary basins."

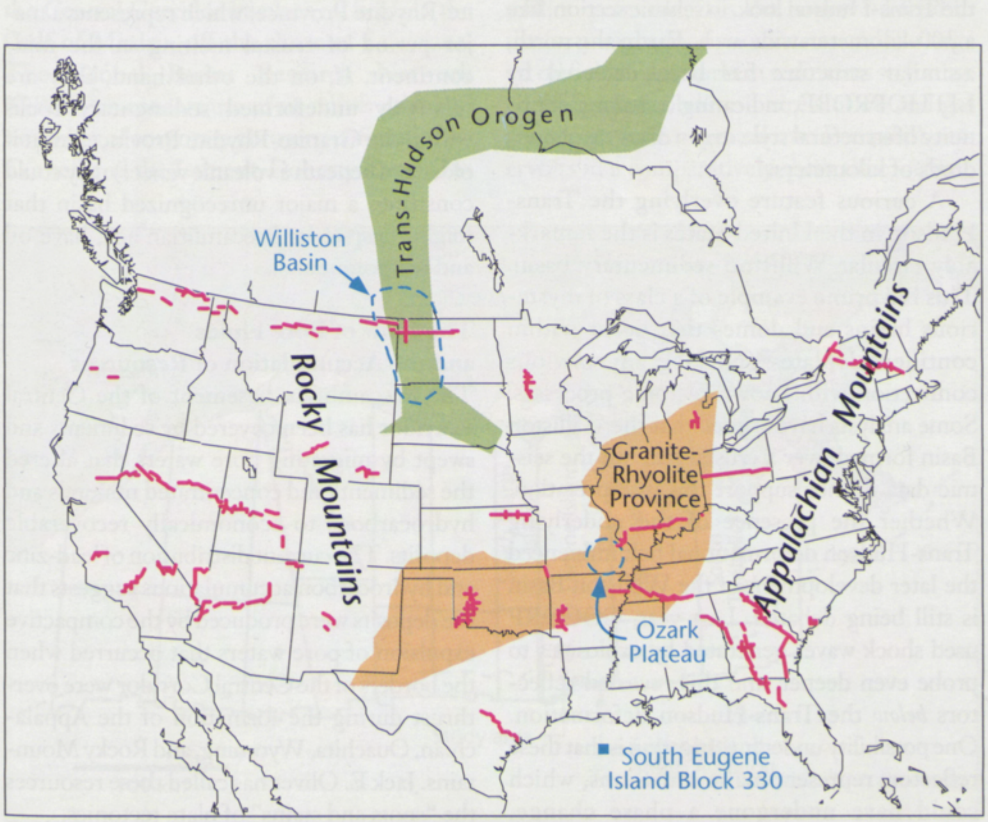


Figure 1. The Central Corridor of North America. Between the Rockies and the Appalachians are a buried Precambrian mountain range (the Trans-Hudson Orogen), extensive Precambrian sedimentary sequences, and economic deposits of lead, zinc, and hydrocarbons.

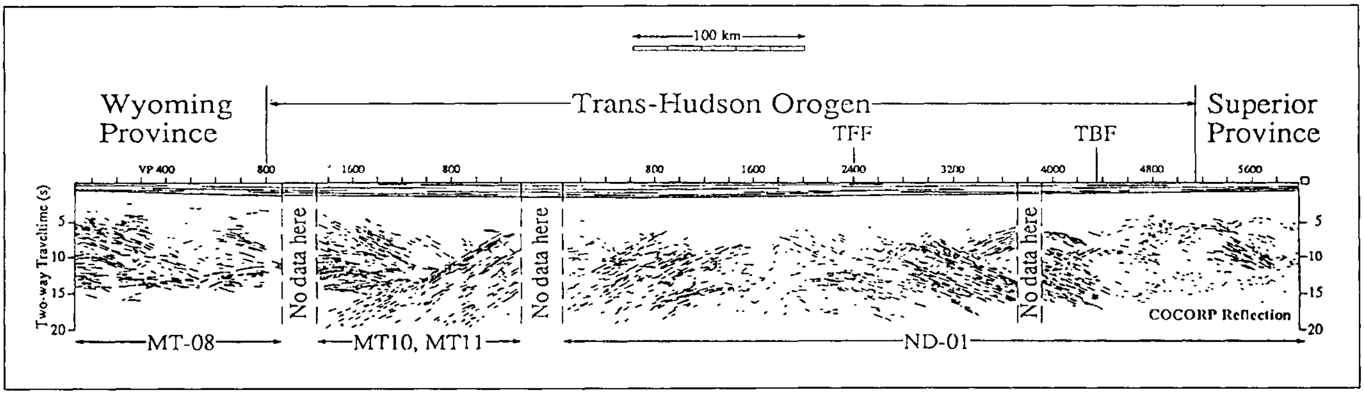


Figure 2. An east-west seismic reflection profile across the Williston Basin in Montana and North Dakota. The 300-kilometer-wide arch in the center is composed of Precambrian crustal material that was caught between converging continents.

further north, in Canada, but buried under the younger sedimentary rocks of the Central Corridor of the United States (see Figure 1). The result of a Precambrian tectonic event, the Trans-Hudson Orogen was formed about 1.8 billion years ago when crustal material was caught between two older colliding blocks—the Churchill Province to the west and the Superior Province to the east. A COCORP transect across this buried feature (Figure 2) shows relicts of the ancient subduction zones dipping under each of the colliding continents. The outward-dipping subduction zones make the Trans-Hudson look, in seismic section, like a 300-kilometer-wide arch. Far to the north, a similar structure has been detected by LITHOPROBE, indicating a striking continuity of structural style over a distance of hundreds of kilometers.

A curious feature overlying the Trans-Hudson in the United States is the remarkably circular Williston sedimentary basin. This is a prime example of a class of mysterious basins and domes that occur within continental plates and lack any obvious connection with known tectonic processes. Some analysts have argued that the Williston Basin formed over a crustal rift, but the seismic data do not support this interpretation. Whether the presence of the underlying Trans-Hudson deformational belt influenced the later development of the Williston Basin is still being debated. Last year, COCORP used shock waves generated by explosives to probe even deeper, and this revealed reflectors *below* the Trans-Hudson deformation. One possibility under investigation is that these reflectors represent mafic intrusions, which could have undergone a phase change, weighting the lithosphere and pulling it down to create the basin's circular form.

Large parts of the eastern and south-central portions of the Central Corridor are underlain by a seismically layered sequence of ancient Precambrian age, which is being investigated by the second author. This sequence is significantly thicker in places than the shallow sediments that overlie and conceal it. The nature of these layered rocks is still a mystery, but they may be either volcanic or sedimentary. If the layers are volcanic in origin, they could reveal the history of the so-called Granite-Rhydite Province, which represents a major period of crustal melting in the midcontinent. If, on the other hand, they are relatively undeformed sedimentary rocks within the Granite-Rhydite Province (even if older and beneath a volcanic veneer) they could constitute a major unrecognized basin that might, despite its Precambrian age, have oil and gas potential.

The Flow of Pore Fluids and the Accumulation of Resources

The Precambrian basement of the Central Corridor has been covered by sediments and swept by migrating pore waters that altered the sediments and concentrated minerals and hydrocarbons to economically recoverable deposits. The current distribution of lead-zinc and hydrocarbon accumulations suggests that the deposits were produced by the compactive expulsion of pore waters that occurred when the borders of the Central Corridor were overthrust during the formation of the Appalachian, Ouachita, Wyoming, and Rocky Mountains. Jack E. Oliver has called these resources the "spots and stains" of plate tectonics.

Present-day groundwater flow in the Central Corridor supports the compactive-expulsion or "squeegee" hypothesis. Water that falls in the Rocky Mountains moves through the Great Interior Planes aquifer system, dissolves salt in Kansas, and ultimately discharges over 1,000 kilometers away in Missouri, where it meets westward-flowing fresh water from the Ozark Plateau (see Figure 4). Daniel Boone retired to a salt spring in this region that is now known as Old Boonslick and extracted salt for sale to other settlers.

The fact that all the salt in the Kansas Aquifers has not been swept out in the sixty million years since the Rocky Mountains were rejuvenated shows that the flow is much too slow to have formed existing lead-zinc deposits. Flows that are fast enough to account for the deposition of these minerals appear to have happened episodically through the expulsion of pore fluids from rock volumes in which the pore fluids had been overpressured by tectonic or sediment loading.

Oil in the Gulf of Mexico: Episodic Natural Refills?

One of the most exciting Cornell projects in the Central Corridor involves oil fields in the Gulf of Mexico, off the shore of Louisiana. The Global Basins Research Network (GBRN), a consortium of six universities and a number of corporate partners, cofounded by Cornell and the Lamont-Doherty Earth Observatory, will start drilling for oil there sometime this summer. The objective is to investigate the way fluids move in sedimentary basins and, perhaps, demonstrate the existence of a new, dynamic kind of oil reservoir.

For the last sixty million years, the Mississippi River has been dumping sediments into the Gulf of Mexico so rapidly that they accumulate at a rate of more than 2 kilometers in depth per million years. The South Eugene Island Block 330 oil field, which is owned and operated by the Pennzoil Company, is in the region of recent, rapid sedimentation. Enclosed in sediments less than 1.5 million years old, it is the largest oil field in the forty-eight contiguous states and the largest oil field in the world in sediments so young.

Since over a billion barrels of oil and gas equivalent have migrated into Pennzoil's reservoirs in a comparatively short time, active

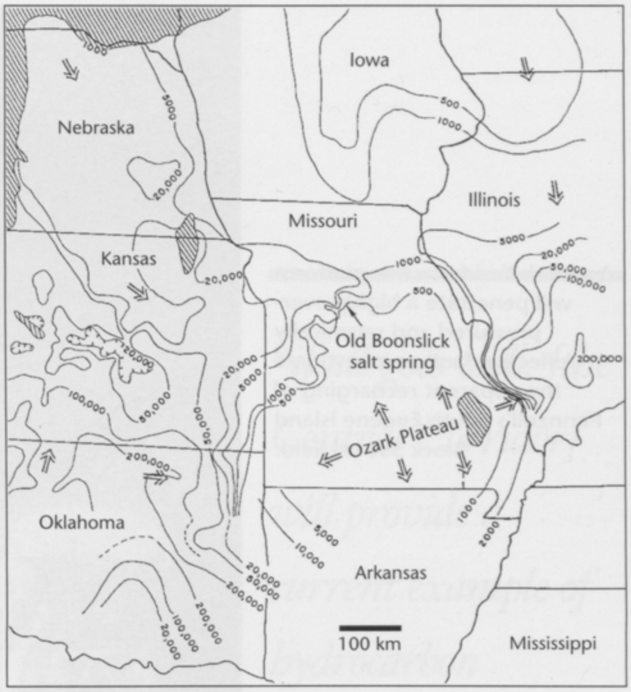


Figure 3. Patterns of salinity in deep aquifers near the Ozark region. Groundwater enters the aquifers in the Rocky Mountains, picks up salt in Kansas, and discharges in saline springs, such as Old Boonslick, when it meets fresh water moving west from the Ozark Plateau. The contour lines indicate salinity in parts per million.

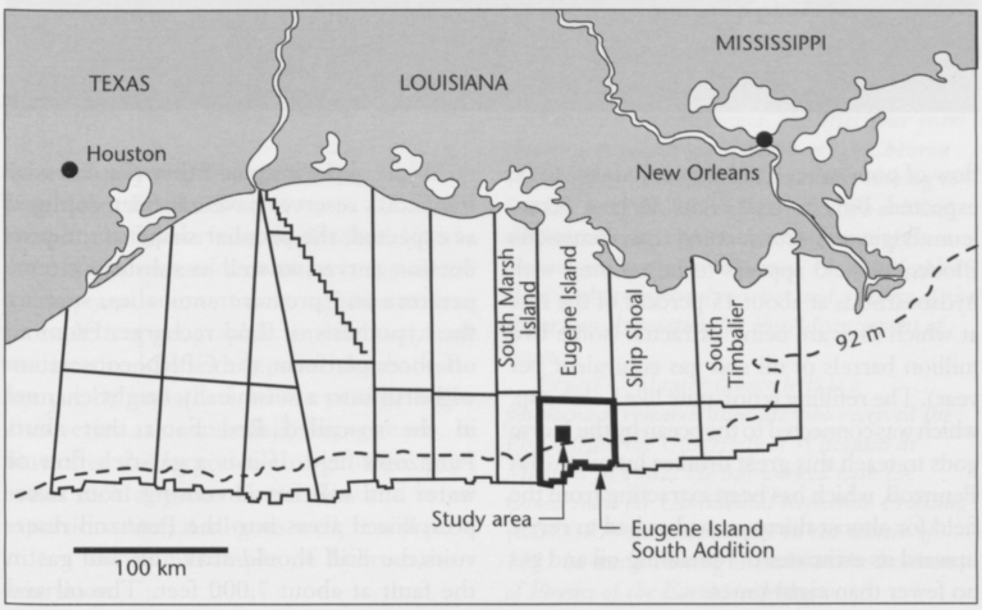
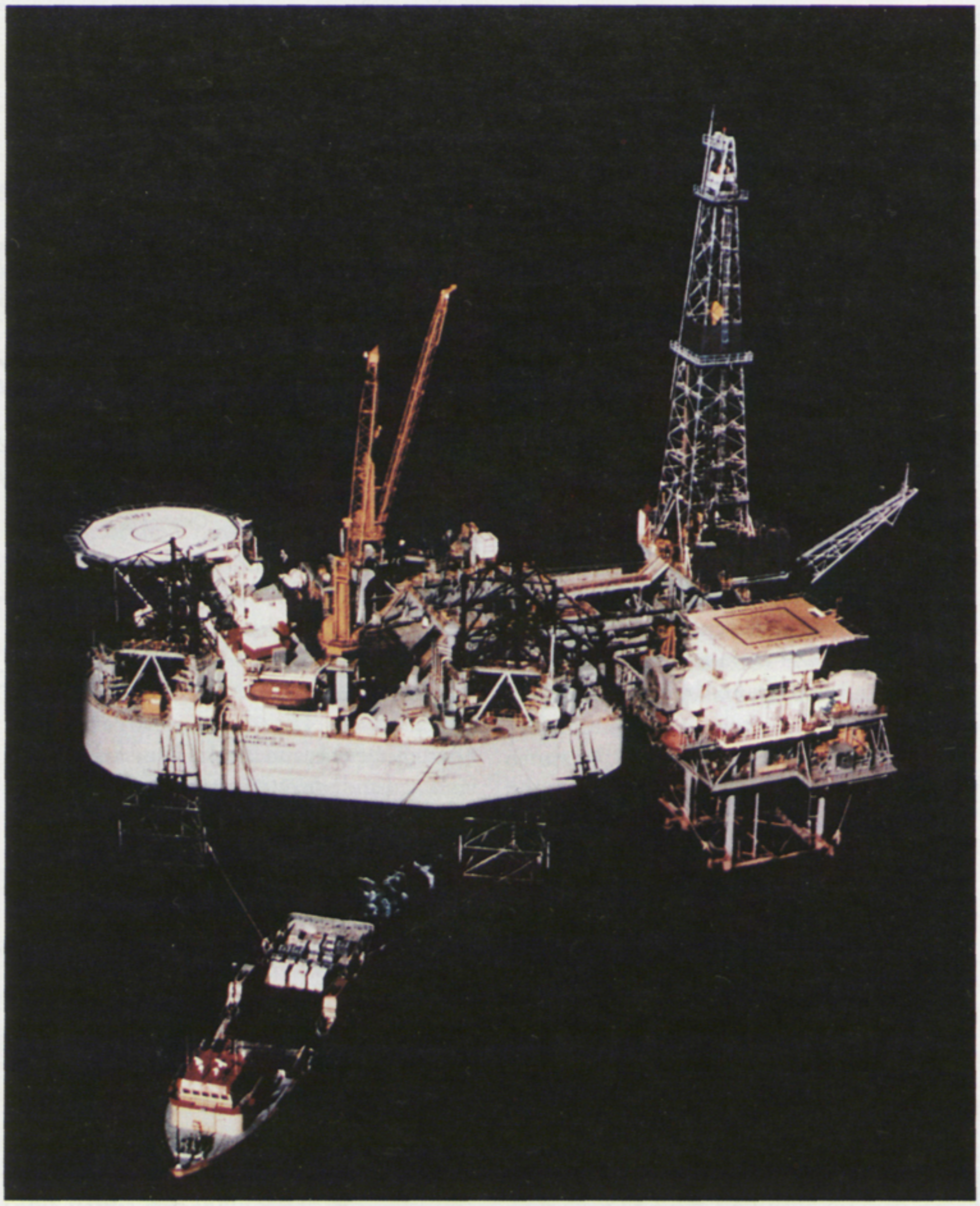


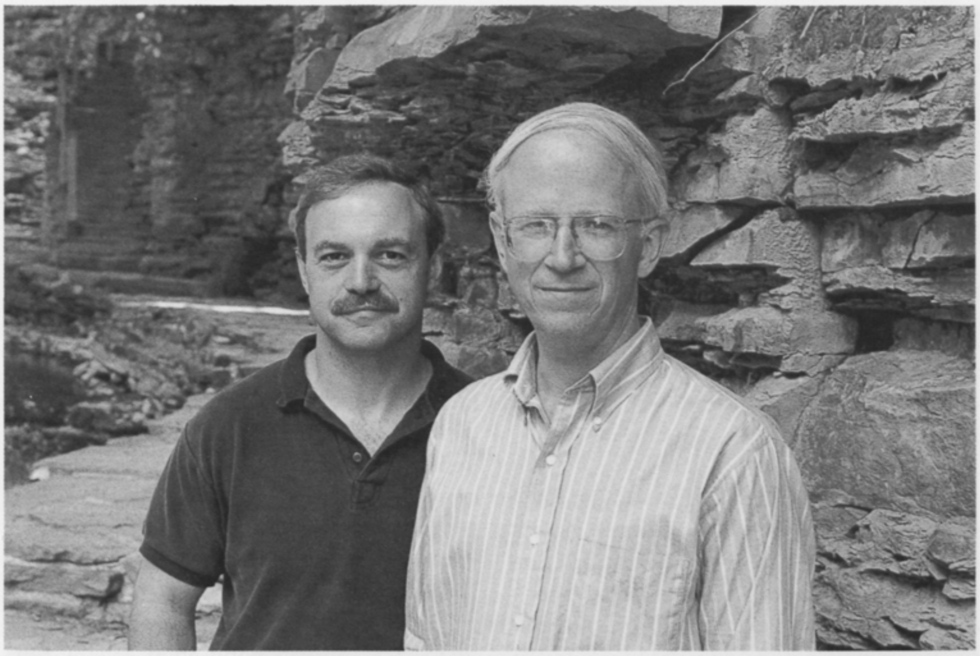
Figure 4. Eugene Island area, Gulf of Mexico. The rapid deposition of silt from the Mississippi River is heating deeper sediments and producing oil and gas, which vent episodically along faults. A study of this process is being conducted by the Global Basin Research Network.

A well drilled from this platform will penetrate a highly overpressured and seismically reflective fault to investigate the apparent recharging of Pennzoil's South Eugene Island Block 330 oil field.



flow of pore water and hydrocarbons is to be expected. But, in what seems to be a petroleum engineer's dream come true, Pennzoil's Block 330 field appears to be refilling with hydrocarbons at about 15 percent of the rate at which they are being extracted (some two million barrels of oil and gas equivalent per year). The refilling is not quite like Loki's cup, which was connected to the ocean by the Norse gods to teach this great drinker humility. But Pennzoil, which has been extracting from the field for almost thirty years, has had to revise upward its estimates of remaining oil and gas no fewer than eight times.

While there may be other reasons why Pennzoil's reserves have not been depleted as expected, the peculiar shape of the production curves, as well as subsurface temperature and pressure anomalies, support the hypothesis of fluid recharge. From an off-shore platform, the GBRN consortium will drill into a seismically bright channel in the so-called Red Fault that abuts Pennzoil's field. If it is a gas-rich flow of water and oil that is venting from overpressurized areas into the Pennzoil reservoirs,the drill should strike oil and gas in the fault at about 7,000 feet. The oil and



gas would be evidence of a seal-rupture/oil-migration event that may be typical of the way oil reservoirs are filled (and lead-zinc deposits produced) in sedimentary basins all over the world.

In addition, a strike in the Red Fault would permit the GBRN to drill a second well. A grant from the Department of Energy (DOE) will cover the cost of the initial drilling. Then, if commercially significant oil is found in the GBRN portion of the hole, the companies involved in the the consortium will reimburse the DOE, which will make the money available to the GBRN so that another hole can be drilled to further investigate the venting phenomena.

Scientifically and Economically Significant Features

Despite its flat surface, the Central Corridor of North America contains many scientifically and economically significant features. It is a geographic, intellectual, and resource frontier with peculiarities that cannot yet be explained, where new geologic discoveries are continually being made. It illustrates the large scale of geologic processes such as groundwater flow and brine expulsion. And, if all goes well, it will provide a current example of hydrocarbon migration.

The progress of the well being drilled by the GBRN will be closely followed in Snee Hall. It will be plotted on a bulletin board for the benefit of the five graduate students and two postdoctoral associates involved in the project, as well as other interested geologists and visitors. If the building erupts in wild cheering sometime in the late summer or early fall, it will mean that oil has been struck.

Lawrence M. Cathles III (above right) has divided his career between industry and academia. After earning the Ph.D. at Princeton in 1971, he spent seven years with Kennecott Corporation. He then joined the faculty of the University of Pennsylvania, but after four years returned to industrial research at the Chevron Oil Field Research Laboratory. Since coming to Cornell in 1987, he has focused on the driving mechanisms and chemical consequences of fluid movements in the earth's crust. He is a member of several professional societies and a fellow of the American Association for the Advancement of Science.

Ernest C. Hauser (above left) is a postdoctoral research associate who received the Ph.D. from the University of Wisconsin at Madison in 1982. He has worked with the Consortium for Continental Reflection Profiling (COCORP) since that time. In the winter of 1991 he was a visiting scientist at the Institute of Physics of the Earth, in Moscow.

"if all goes well, [the Central Corridor] will provide a current example of hydrocarbon migration."

DEEP-FOCUS EARTHQUAKES

by William A. Bassett

"inferences must be drawn from remote evidence interpreted in accordance with processes that can be observed in the laboratory."

The interior of the earth is a difficult place to do fieldwork. One cannot pack up and go there when classes are out. Instead, geological inferences must be drawn from remote evidence interpreted in accordance with processes that can be observed in the laboratory.

Geophysicists believe that when the earth formed, much of its substance came from a mix of materials that can still be found in certain meteorites, called carbonaceous chondrites. These are exotic mixtures of spherules of various minerals with fine-grained dust that contains a wide range of materials from metallic iron and nickel to amino acids. What has happened to these materials over the course of the earth's history and how they behave today are subjects of ongoing research.

Since seismic waves produced by earthquakes are affected by the materials through which they travel, they can be made to yield information about physical properties such as density, viscosity, and compressibility. But in order to use this information to understand the earth's interior, it is necessary to know what happens to minerals at the temperatures and pressures found there. This is where experimentalists come in. By measuring such properties as crystal structure, density, compressibility, thermal expansivity, and sound velocities as functions of pressure and temperature, they provide information that makes it possible to interpret the evidence.

The crucial piece of equipment, which can achieve the pressures that prevail in the earth's interior, is the diamond-anvil cell. A tiny sample of material to be studied is placed between the faces of two perfectly faceted gem-quality diamonds, and these anvils are squeezed together by turning a screw. When the desired pressure has been attained, the sample can be heated with electrical resistance or a focused laser beam. X-ray diffraction can be used to reveal the structure and density of a crystalline material while high pressure and temperature are maintained, or the sample can

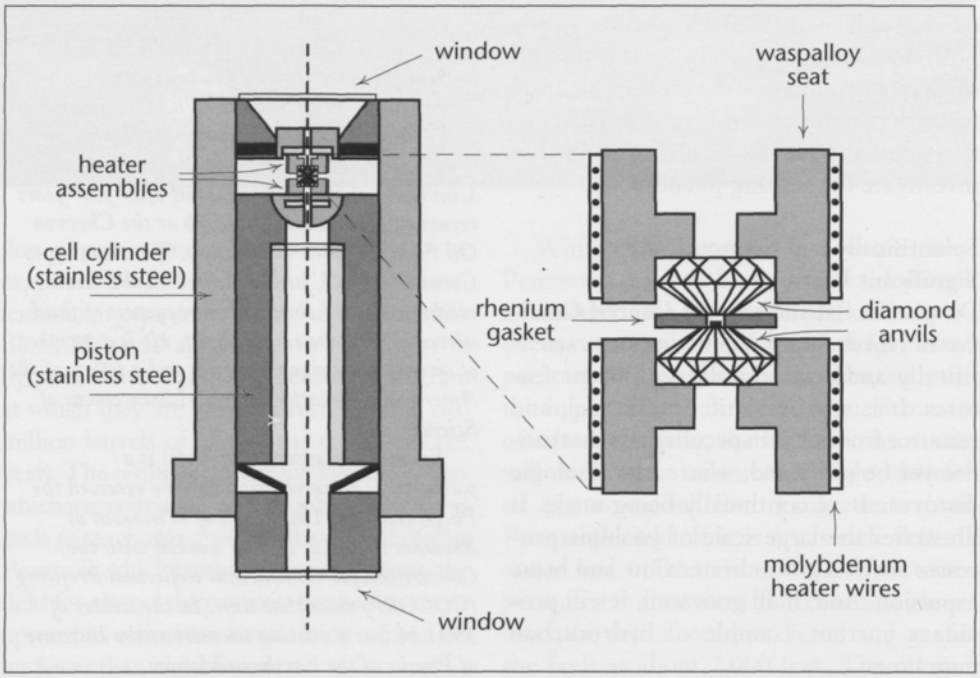


Figure 1. A diamond-anvil cell, in which samples are subjected to high pressure and temperature. For high-stress experiments, the rhenium gasket is left out.

be examined by optical or electron microscopy after it has been removed from the diamond cell.

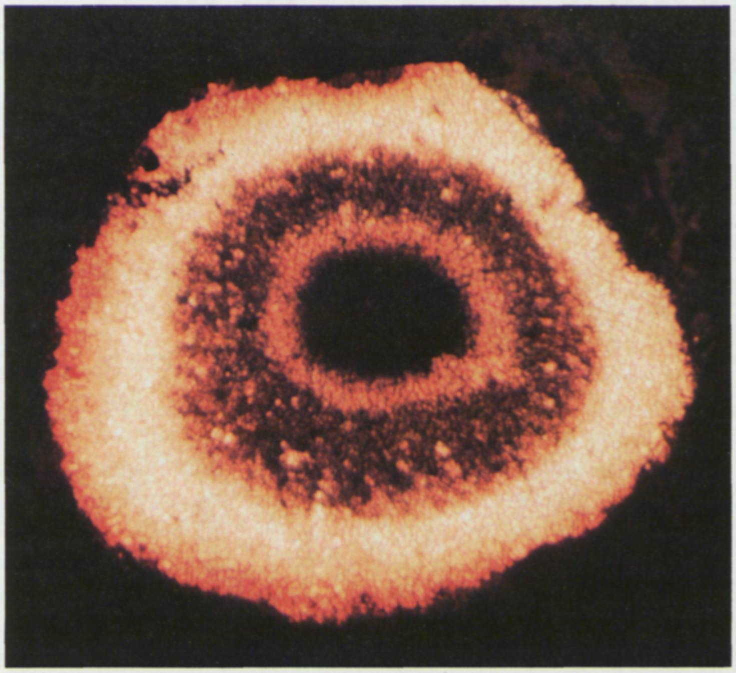


Figure 2. Fe_2SO_4 under pressure between diamond anvils. Rings show that both pressure and shear deformation are required to make the phase transition take place.

One interesting problem is the origin of deep-focus earthquakes. Earthquakes closer to the surface result from brittle failure, when rocks under stress break and slip. But deep-focus earthquakes occur at depths of 400 to 600 kilometers, where rocks lack the strength to undergo brittle failure, although their seismic signals suggest a similar type of shearing motion. Nearly all deep-focus earthquakes occur in subduction zones, where mantle material is descending into the earth's interior. It has been suggested that phase transitions in the subducting rocks might be responsible for these earthquakes, but it has not been clear how they could trigger the release of so much energy so suddenly.

Graduate student Terrance Wu is studying this problem by making detailed observations of phase transitions in olivine, $(Mg,Fe)_2SiO_4$, which is the major constituent of subducting rocks. Using synchrotron radiation and optical microscopy to observe samples as they are squeezed and heated, he has made some startling discoveries. Most interesting is the finding that samples go through phase transitions at a much lower temperature if they are subjected to strong shear deformation. When a sample of iron-rich olivine silicate is compressed in the diamond-anvil cell, a brown ring appears. The sample extrudes as it is squeezed, which results in a high pressure in the center, diminishing toward the periphery. The extrusion also causes shear deformation, and the ring forms in the region where the combination of pressure and shear deformation brings about a phase transition. In the center, where the pressure is high but the shear deformation is low, no change occurs. Likewise, outside the ring, where the shear deformation is great but the pressure is too low, no change takes place.

These results suggest that olivine descending into the earth's deep interior may undergo a gradual increase in pressure until it enters the stability field of the high-pressure phase while remaining metastable in the low-pressure phase, on the verge of transition. Once a transformation is triggered in a small area, it would increase the shear deformation in adjacent regions, resulting in further transformation. This feedback loop would lead to the runaway release of stored-up strain energy from a large volume of metastable olivine—an event that would certainly qualify as an earthquake.

William A. Bassett is a mineralogist specializing in phase transitions under high temperature and pressure. He received the Ph.D from Columbia University in 1959, and taught at the University of Rochester before coming to Cornell in 1978. He is a fellow of the American Association for the Advancement of Science, the American Geophysical Union, the Geological Society of America, and the Mineralogical Society of America.

MANTLE PLUMES AND OCEANIC VOLCANISM

by William M. White

"plate tectonics provides no direct explanation for volcanism at hot spots"

Volcanism is one of nature's most spectacular phenomena, and the explosions of Thera, Vesuvius, Krakatoa, and Pelée rank among history's great natural disasters. From time immemorial, erupting volcanoes have inspired fear and awe. But only recently have geologists begun to understand the processes that give rise to volcanoes.

From the perspective of plate tectonics, volcanism occurs in three settings: at divergent plate boundaries (such as the Mid-Atlantic Ridge and the East Pacific Rise), along island arcs associated with subduction zones at convergent plate boundaries (such as the Aleutians or the Japanese archipelago), and in association with "hot spots" that may occur either within plates (Hawaii) or along divergent plate boundaries (Iceland), where it is distinct in both composition and volume from normal plate-boundary volcanism. Volcanism at the boundaries of divergent plates and convergent plates can be explained in terms of the physics of tectonic processes. But plate tectonics provides no direct explanation for volcanism at hot spots, and this puzzling phenomenon has become a focus of my research.

Hot spots seem to involve columns of hot rock that rise buoyantly from deep in the earth's mantle. As these "mantle plumes" approach the surface, decompressional melting occurs, much as it does at mid-ocean ridges, and the resulting magma makes its way through the crust, producing volcanoes. Mantle plumes appear to remain stationary for great periods of time, while crustal plates slowly pass over them. This can result in a chain of volcanoes marking a succession of different places where a mantle plume has "burned through" the crust. There are a number of plumes beneath the Pacific Ocean, and the northwestward motion of the Pacific Plate has left several parallel trails of volcanic islands and seamounts (see Figure 1). Active volcanoes occur only at the southeastern ends of these chains.

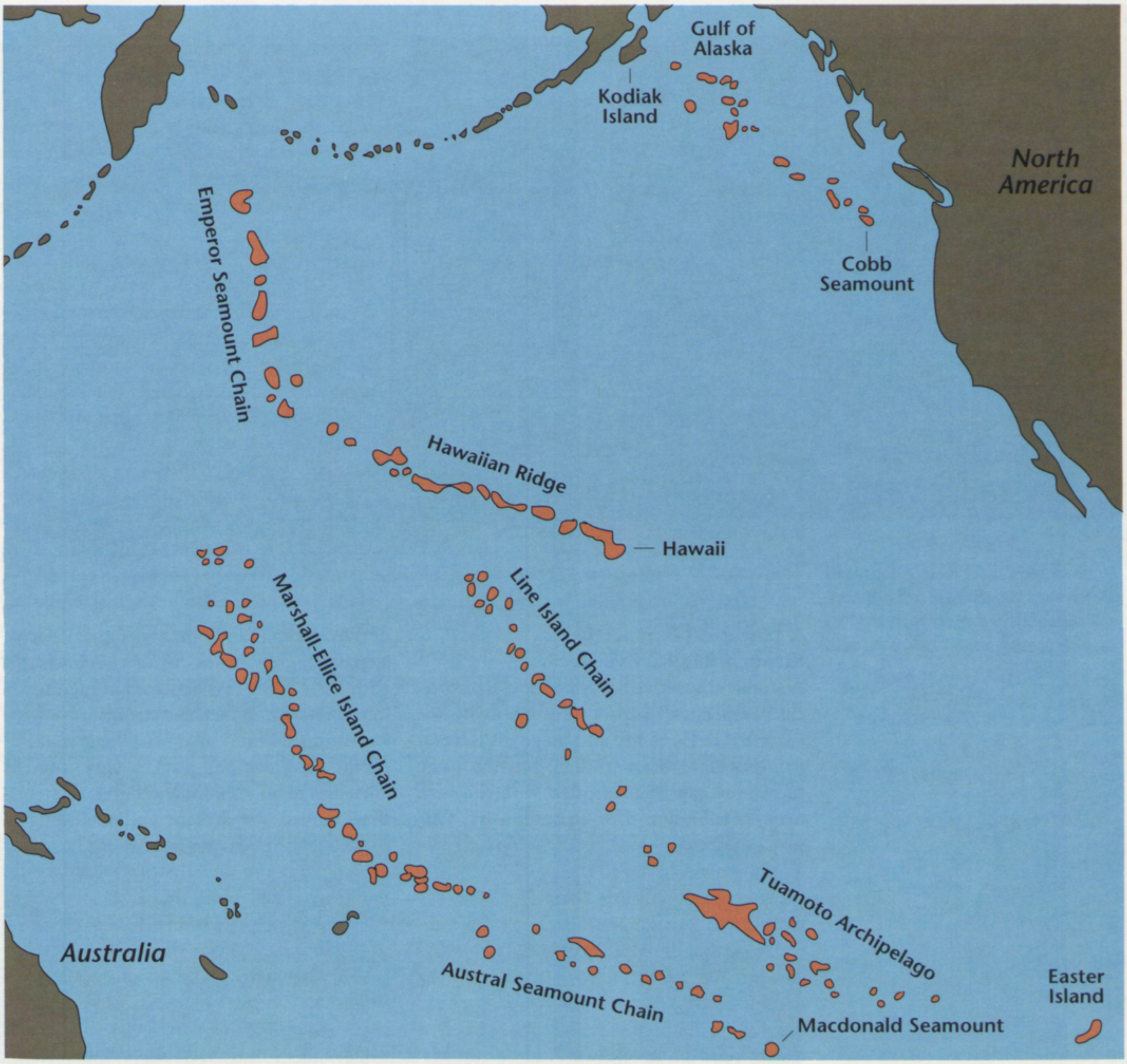
The fact that the plumes remain stationary suggests that they must arise deep in the mantle, well below the region of convection responsible for the motions of the crustal plates. Numerical convection models have revealed that plumes only occur when a heat source is placed at the bottom of a convecting region, and do not occur when the heat source is within the convecting medium. This suggests that mantle plumes may rise from the core-mantle boundary, nearly 3,000 kilometers beneath the earth's surface. According to recent calculations, the heat flux of all mantle plumes matches the estimated flux from the earth's core, suggesting that mantle plumes may be the chief mechanism by which the core is cooled.

The Chemistry of Magmas and the Chemistry of the Mantle

Magmas that rise in volcanoes can be used to make inferences about the chemistry of the mantle from which they are derived. Of particular interest are certain elements, such as potassium, rubidium, and niobium, which are severely depleted in magmas erupted at mid-ocean ridges, but are found in high concentrations in the earth's continental crust.

The best explanation of this difference seems to be that these elements are not readily accepted into the structure of the mantle's constituent minerals because of the size or the charge of their ions. Rubidium, for example, has an ionic radius of 1.5 Å, while available site radii generally do not exceed 1.0 Å, and niobium has a charge of +5, while the elements for which it might substitute have charges of +2 or +3. When mantle melts, the "incompatible elements" present in it tend to enter the liquid phase.

Throughout most of its depth, the mantle is solid, although it is sufficiently plastic for



convection to occur at an extremely slow pace. Only in the upper 100 to 200 kilometers are temperatures high enough and pressures low enough for melting to occur. Repeated episodes of magmatism throughout the earth's history have removed incompatible elements from this upper part of the mantle and concentrated them in the crust. Inasmuch as the oceanic crust is continually recreated from the depleted upper mantle at spreading centers, it does not constitute a large reservoir for incompatible elements. Incompatible elements transported from the mantle to the continental crust accumulate there.

Magmas from mantle plumes are not as depleted in incompatible elements as magmas from spreading centers, even when they erupt on volcanic islands far from the nearest continental plates. This suggests that the plumes originate much deeper than the depleted upper level of the mantle. Some plumes are actually enriched in incompatible elements, providing an important clue to their origin.

Figure 1. The Pacific Ocean. Volcanic islands and seamounts are produced in parallel chains as the Pacific Plate moves northwest over fixed mantle plumes.

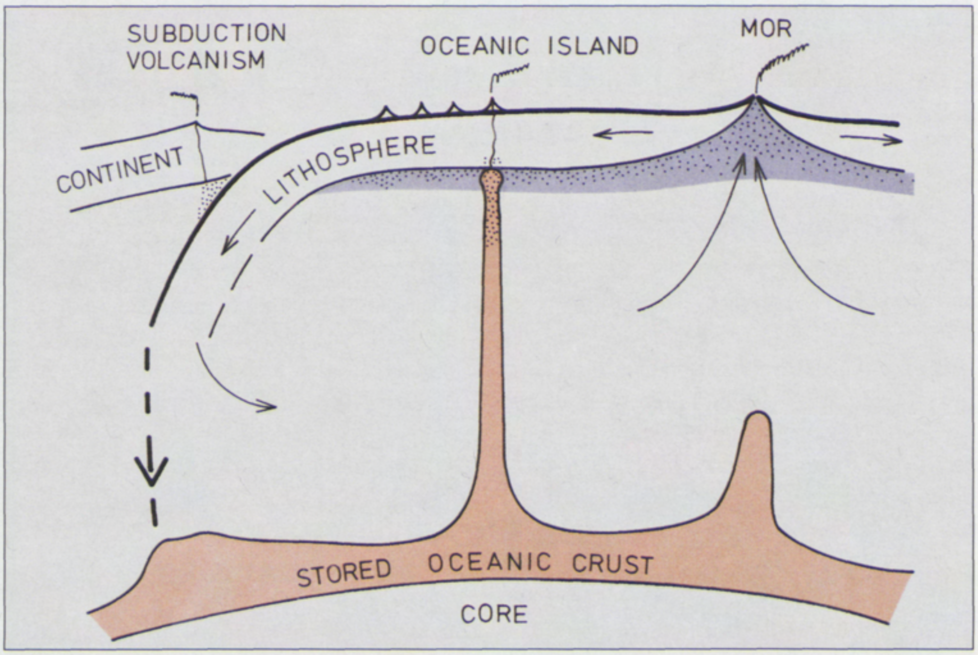


Figure 2. The recycling of oceanic lithosphere. When basalt of the oceanic crust is subducted, it is transformed into a dense metamorphic rock called eclogite. This sinks to the core-mantle boundary, where heating reduces the density and causes it to rise as mantle plumes.

A Historical Perspective through Radioactive Decay

Natural radioactive decay provides a historical perspective on processes involving incompatible elements and magmas. Several isotopes have been studied, but the basic technique can be illustrated with the beta decay of rubidium-87 to strontium-87. This process is very slow, since rubidium-87 has a half-life of fifty billion years. The daughter element, strontium, is much more compatible in mantle minerals than rubidium; for instance, it readily substitutes for the calcium in pyroxene. Thus, episodes of melt extraction that have depleted the upper mantle of rubidium have a smaller effect on the amount of strontium. The longer rubidium-87 stayed in the mantle before segregating out, the more strontium-87 was built up by radioactive decay. This means that the ratio of strontium-87 to its sister isotope, strontium-86, is a function of the time that has elapsed since melt extraction occurred. If the episode was ancient, the ratio is small, but if it was more recent, the ratio is larger.

The very low ratio of strontium-87 to strontium-86 found in magmas from mid-ocean ridges indicates that the depletion of rubidium relative to strontium happened billions of years ago. In contrast, magmas derived from mantle plumes typically have slightly higher ratios, which is consistent with their being less depleted in incompatible elements. In fact, the strontium-87-to-strontium-86 ratio in at least some mantle-plume magmas suggests a very ancient enrichment in rubidium relative to strontium. Given our present understanding of the earth, this enrichment must have occurred when the rock that is now in mantle plumes was near the surface.

My colleague Albrecht Hofmann and I suggested that mantle plumes may be composed of anciently subducted oceanic crust and lithosphere (see Figure 2). Oceanic crust is produced by magmatism at mid-ocean ridges and is enriched in iron and incompatible elements relative to the upper mantle from which it comes. Sediments eroded from continents and deposited in the ocean add yet more incompatible elements. Eventually, the oceanic crust is subducted. (Very little of the vast amount of oceanic crust produced throughout the earth's history has been preserved on continents.) Under pressure, it metamorphoses into eclogite (the high-pressure equivalent of basalt). It becomes denser than mantle, and because it is relatively rich in iron, it remains so at all higher pressures. Thus, we believe, subducted oceanic crust may sink to the bottom of the mantle and accumulate at the core-mantle boundary. There, energy from the core would slowly heat it until, after perhaps hundreds of millions of years, thermal expansion would make it less dense than overlying mantle so that it could rise to the surface in the form of mantle plumes.

The Galápagos Islands: A Study of Plume Configuration

Most plumes form linear chains of volcanoes that show a simple age progression. But not all oceanic islands conform to this simple pattern. The Galápagos Islands, whose unusual flora and fauna were so fascinating to Darwin, are among the most exceptional. The Galápagos group consists of ten major volcanic islands and a number of lesser remnant volcanoes that emerge from a broad, shallow submarine platform (see Figure 4). While two aseismic ridges, the Cocos and Carnegie Ridges, extend from the archipelago in directions consistent with the motion of the Cocos and Nazca Plates, the emergent volcanoes do not form a linear chain. Nor is there any simple geographic pattern to the ages of the volcanoes, although the oldest tend to occur in the southeastern part of the archipelago. Of the nineteen emergent volcanoes in the Galápagos, nine have been active historically and four others have probably erupted in the last ten thousand years. By comparison, only six Hawaiian volcanoes are active.

This abundant recent volcanism and its broad distribution have allowed us to map the geochemistry of the underlying mantle. Previous maps of geochemical variation

Figure 3. Pillow lava from the East Pacific Rise. Rapid quenching of lava that erupts under cold sea water results in the pillow shape.

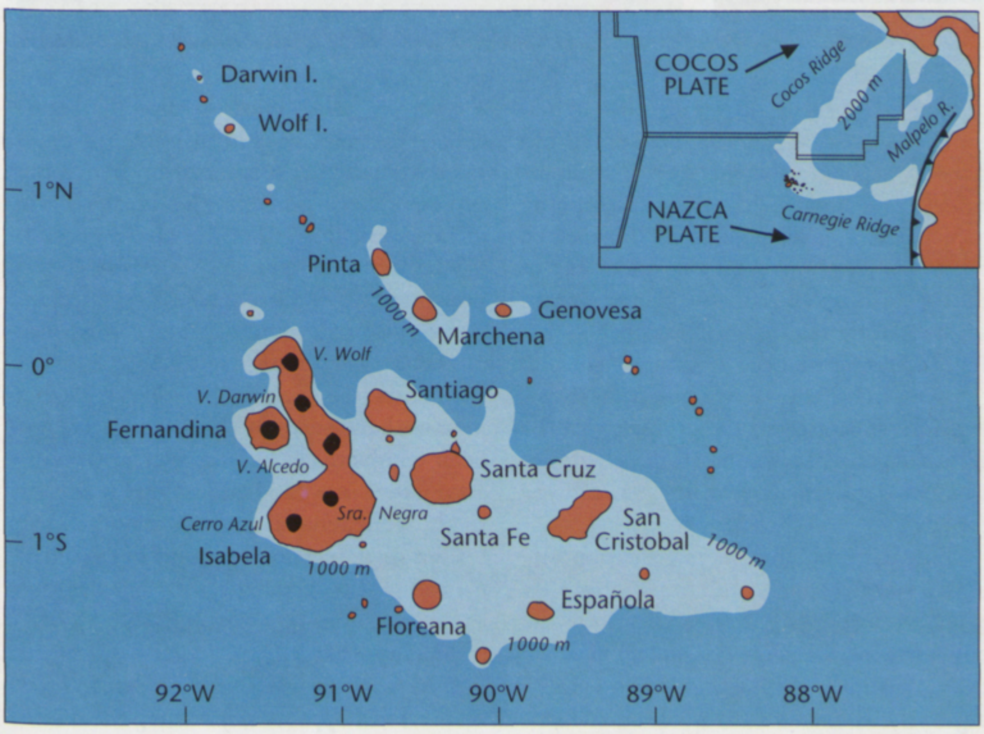
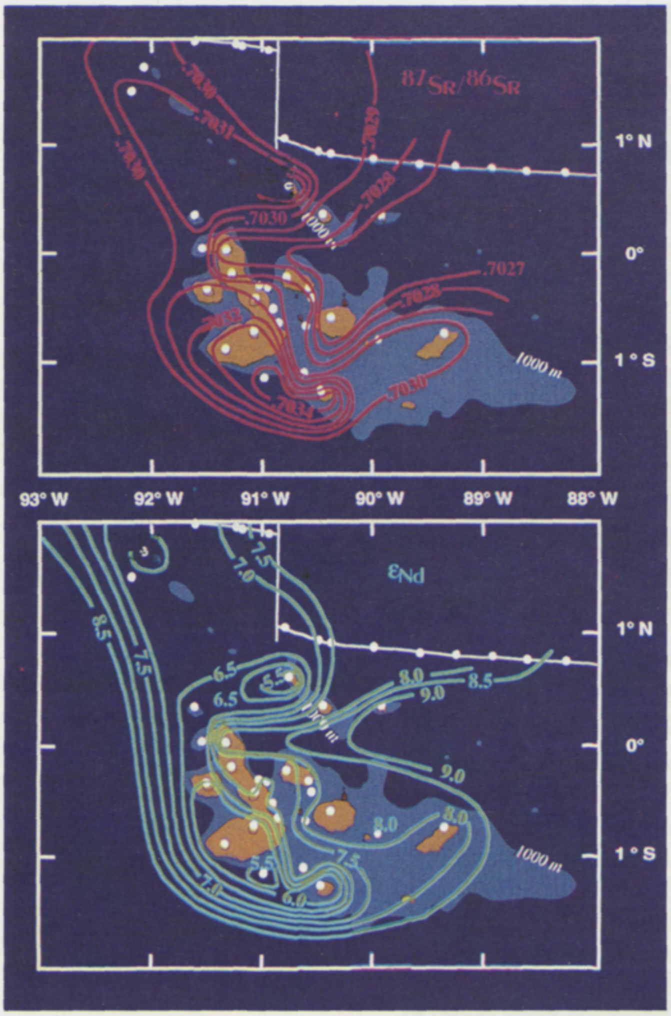


Figure 4. The Galápagos archipelago. The inset shows the location of the Galápagos in the eastern equatorial Pacific.



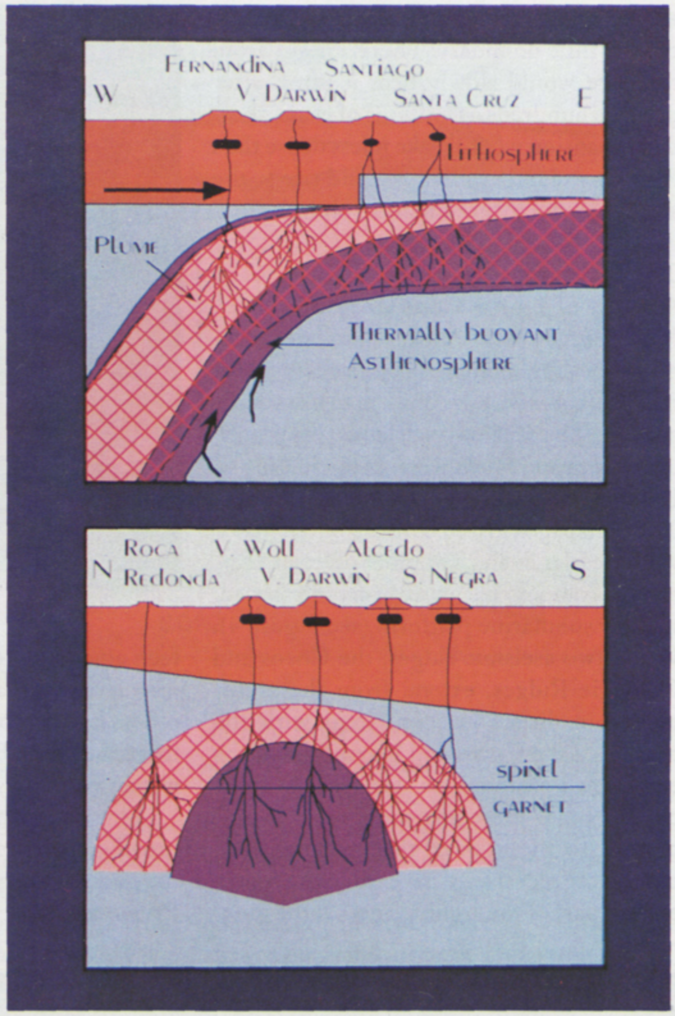


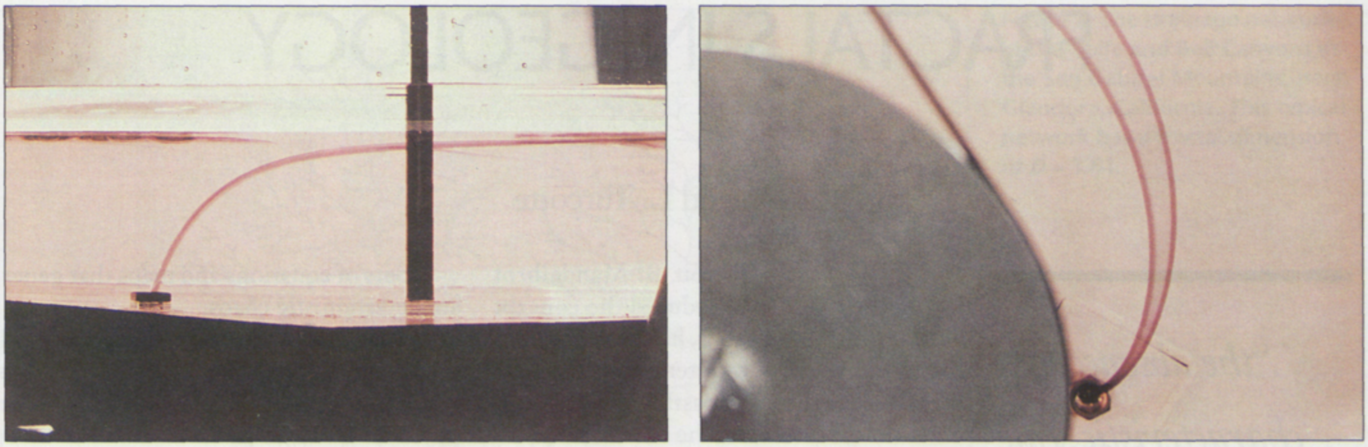
Figure 5 (left). Contours marking isotope ratios in lavas from the Galápagos. The ratio of ^{87}Sr to ^{86}Sr and the ratio of ^{143}Nd to ^{144}Nd, derived from the analysis of more than 175 lava samples, show regional variation in the underlying mantle.

Figure 6 (right). The bent-plume model of the Galápagos. Material from the upper mantle becomes entrained by the bent plume, as shown in east-west and north-south cross sections.

around Iceland and the Azores showed that these islands ride plumes that spread out laterally (though not necessarily symmetrically) and mix with the surrounding depleted upper mantle, as might be expected of plumes impinging on the underside of the rigid lithosphere. But geochemical maps of the mantle beneath the Galápagos (see Figure 5) show that the most incompatible-element-rich material defines an east-facing horseshoe around the periphery of the archipelago, while the most incompatible-element-depleted mantle lies beneath the center.

This pattern, which is just the opposite of that seen in Iceland and the Azores, may result from fluid-dynamic processes in the upper mantle. The Nazca Plate, upon which the Galápagos volcanoes are built, is moving to the east-southeast at about 6 centimeters per year. The soft, fluid asthenosphere that underlies lithospheric plates is viscously coupled to them, and hence the asthenosphere beneath the Nazca Plate must also be flowing to the east-southeast. We believe that a plume rising through the flowing asthenosphere is bent by its motion, just as a smoke plume rising through the atmosphere is bent by wind. Laboratory experiments (see Figure 7) show that when a plume is bent, surrounding material that has been conductively heated by it will be incorporated into the center. This is similar to the geochemical pattern found in the Galápagos: volcanoes tapping the original mantle plume occur in a horseshoe around the central region, where volcanoes tap entrained upper mantle.

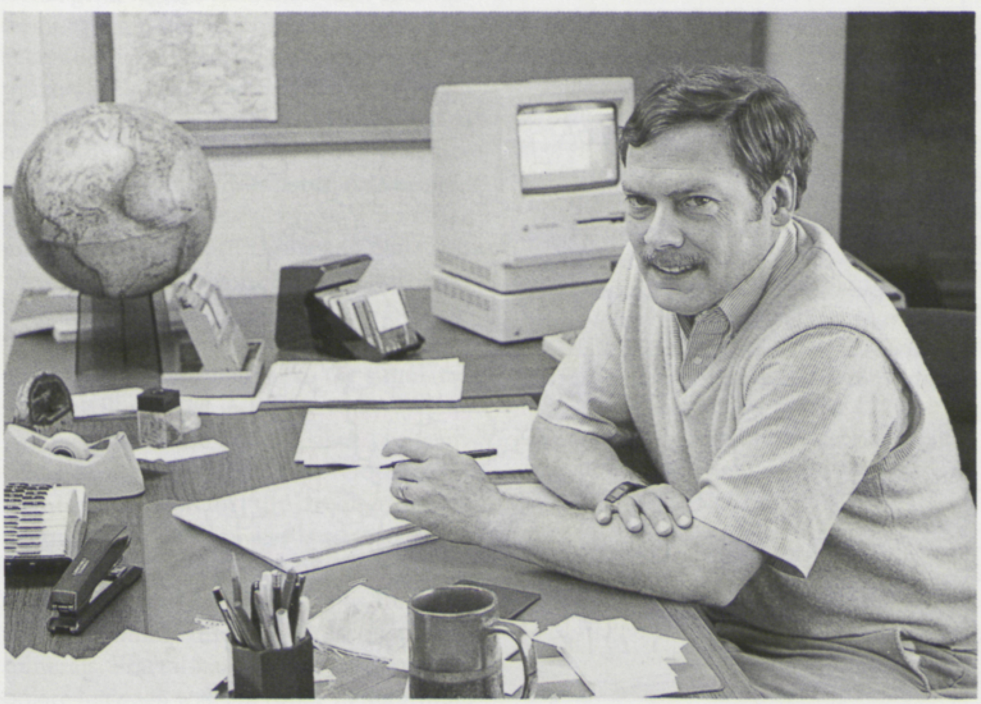
The Galápagos hot spot appears to offer an excellent opportunity to map the distri-



bution of melting in the mantle, and this will be the subject of further research. We know that both degree of melting, which is typically in the range of 5 to 20 percent, and depth at which melting occurs—typically 20 to 60 kilometers—affect the chemistry of magmas. Thus, a painstaking analysis of erupted magmas will make it possible to determine, with a simple inversion algorithm, the percentage and depth of melting. These findings will test our model of the fluid-dynamic interaction of the plume and upper mantle beneath the Galápagos.

William M. White is a geochemist whose research involves interpreting subtle chemical clues to the large-scale behavior of the earth. After receiving the Ph.D. from the University of Rhode Island in 1977, he did postdoctoral work at the Carnegie Institution of Washington and at the U.S. Geological Survey in Denver. He spent five years as a staff scientist at the Max Planck Institut für Chemie in Mainz, Germany, and a year in the College of Oceanography at Oregon State University before joining the faculty at Cornell in 1986. He is a member of the Geochemical Society, the American Geophysical Union, the European Union of Geosciences, and the Oceanography Society.

Figure 7. Laboratory experiment illustrating the effect of asthenospheric motion on a rising mantle plume. The plume is simulated by hot, red corn syrup rising from the bottom of a tank filled with cool, clear corn syrup. Motion is induced by rotating a plexiglass plate (analogous to the rigid lithosphere) on top of the corn syrup. The side view, on the left, shows how the plume is bent by asthenospheric motion. The top view, on the right, shows how the original plume material becomes concentrated on the periphery as asthenosphere is entrained into the center.



FRACTALS IN GEOLOGY

by Donald L. Turcotte

"the absence of a characteristic scale (length or time) in a problem directly implies fractal statistics."

When Benoit B. Mandelbrot first introduced the concept of fractals, he did so in a geological context, calling attention to the scale invariance of a rocky coastline. When such a coastline is measured, the shorter the measuring rod, the longer the coastline. The length of the coastline L and the length of the rod r scale as a power law $L \sim r^{1-D}$, where D is the fractal dimension. For a typical coastline, $D \approx 1.2$.

Scale invariance implies the applicability of fractal statistics. A power-law (fractal) distribution is the only distribution that does not introduce a characteristic dimension. Thus, the absence of a characteristic scale (length or time) in a problem directly implies fractal statistics. In addition, many modern approaches to extended nonlinear systems result in fractal statistics. Examples include:

- Sets of equations and maps that generate deterministic chaos;
- The renormalization-group approach for which Kenneth Wilson (who was then at Cornell) received the Nobel Prize in physics;
- Statistical models such as percolation clusters and diffusion-limited aggregation; and
- Self-organized criticality.

Drainage networks, which have the form of fractal trees, are an excellent example of fractals in geology. The nearly universal structure and fractal statistics of drainage networks suggest that they are generated by a well-defined physical process. Scale-invariant models based on percolation clusters, diffusion-limited aggregation, and self-organized criticality have all been used to generate computer simulations of drainage networks.

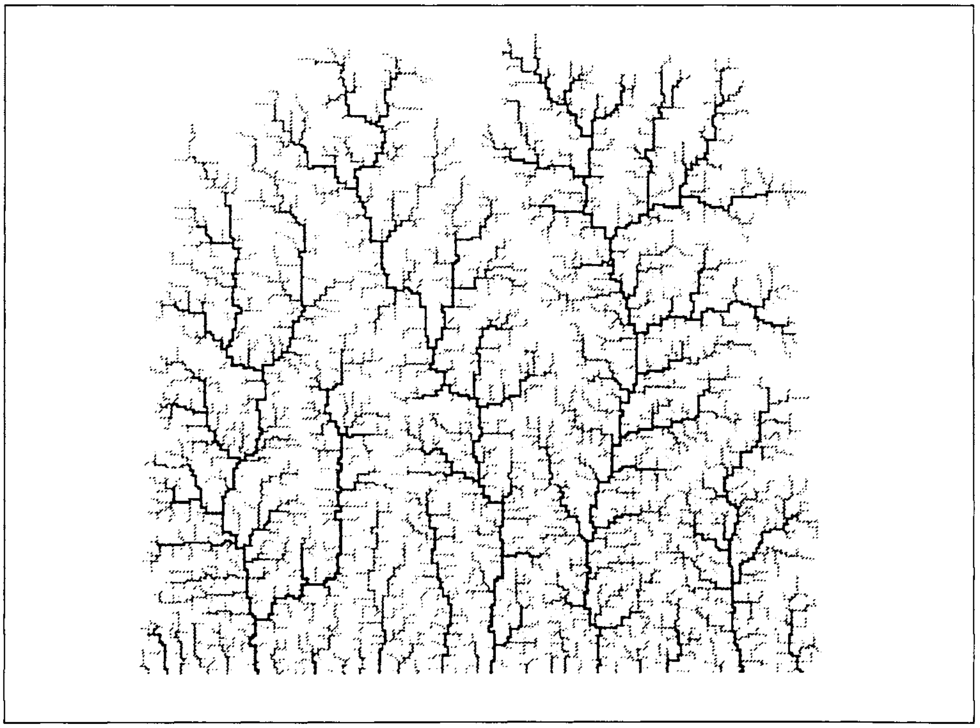


Figure 1. A simulated drainage network. The pattern is generated by random walkers that move back and forth across the surface; whenever they encounter a canyon, it is extended. Based on the number and length of tributaries, the network has a fractal dimension of $D = 1.90$.

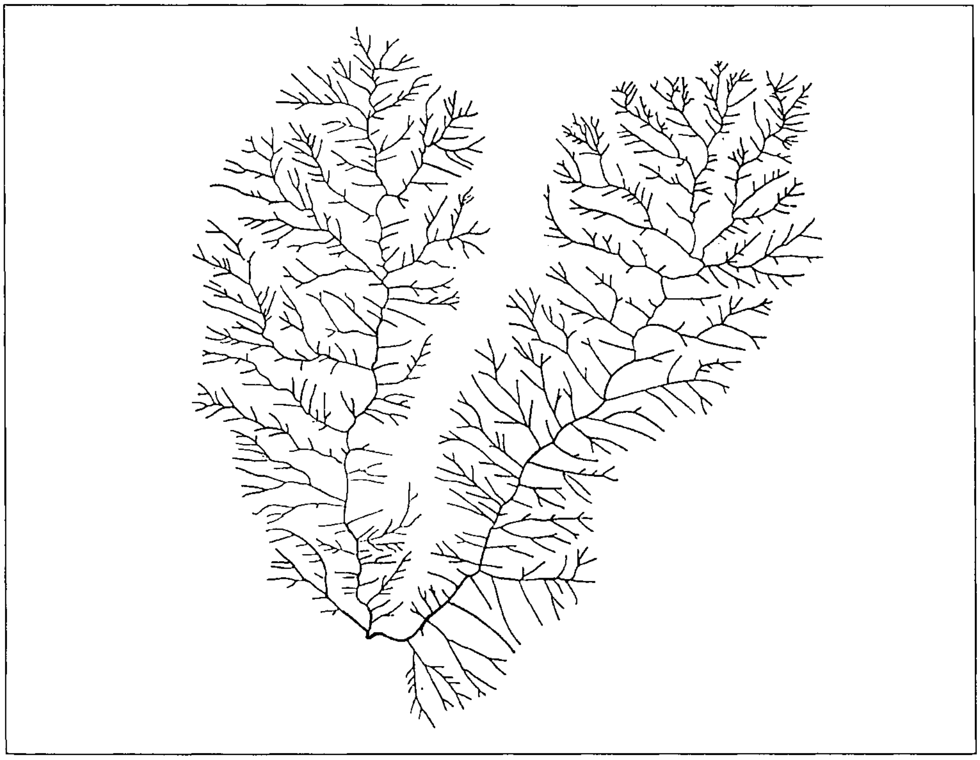


Figure 2. The drainage network of the Volfe and Bell Canyons in the San Gabriel Mountains, near Glendora, California. This typical network has a fractal dimension of $D = 1.81$.

A model produced through the use of diffusion-limited aggregation is shown in Figure 1. Seed canyons are introduced on the lower boundary. Random walkers are randomly introduced on the two-dimensional grid; when a random walker encounters a canyon, the canyon is extended. The accumulation of forty thousand random walkers yields the result shown.

The model simulates the headward migration of drainage networks that has been observed in arid climates. An example of a real drainage network is shown in Figure 2, a field map of the Volfe and Bell Canyons in the San Gabriel Mountains, near Glendora, California. As can easily be seen, the network has well-defined fractal properties that are very similar to the simulated network illustrated in Figure 1.

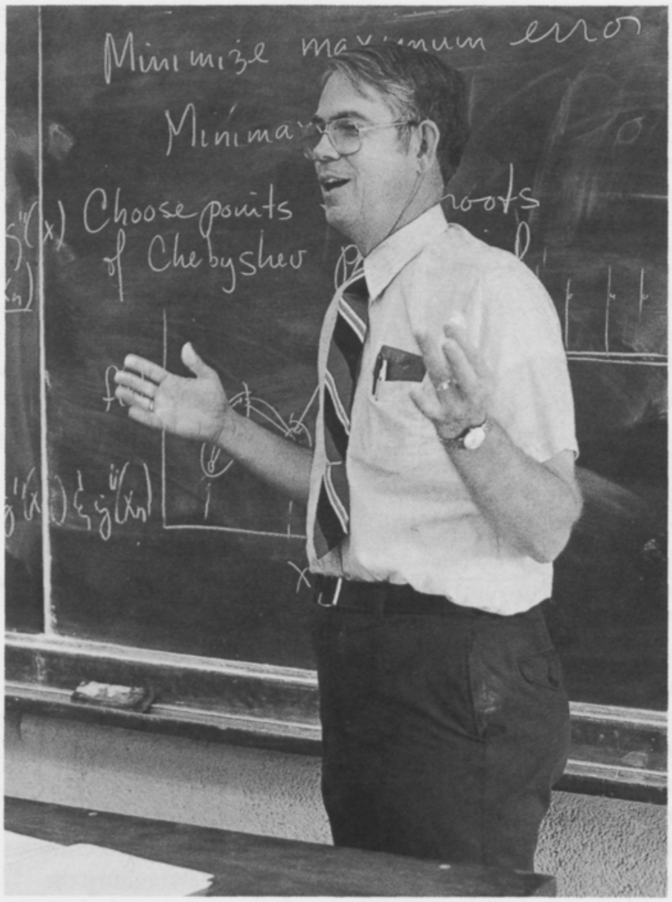
Fractals are also proving useful in many other areas of geology. The Gutenberg-Richter relation for the frequency and magnitude of earthquakes is a fractal. The frequency-size distribution of volcanic eruptions is a fractal. Fractal statistics are being used to estimate reserves of petroleum and minerals. Fractal statistics are used to interpolate between wells in order to determine the three-dimensional structure of petroleum reservoirs. Fractals and related concepts provide a basis for understanding the geometrical form of mountains and many other fundamental geological phenomena.

Donald L. Turcotte is a specialist in fluid mechanics who received the doctorate from the California Institute of Technology in 1958 and served on the faculty of Cornell's Graduate School of Aerospace Engineering before moving to the Department of Geological Sciences in 1973. He is interested in the application of dynamical systems to geological problems, such as the mechanisms that drive the movement of tectonic plates. He is a fellow of the American Geophysical Union and the Geological Society of America; in 1984 he was elected to the National Academy of Sciences. From 1981 to 1990 he chaired the department. His book, Fractals and Chaos in Geology and Geophysics, *is available in paperback from Cambridge University Press.*

■ With the death of ***George F. Scheele*** on February 13, Cornell lost one of its most beloved professors. A faculty member of the School of Chemical Engineering since 1962, he was fifty-seven when he succumbed to complications following a liver transplant.

Scheele was a distinguished scientist, whose research centered on instabilities in fluid flow and the coalescence of drops in fluid streams. He was an effective teacher, who won the Excellence in Teaching Award (given by Tau Beta Pi and the Cornell Society of Engineers) in 1970. He was an able administrator, serving as associate director of the School of Chemical Engineering from 1982 until the time of his death. He was a successful fund raiser, who played a crucial role in persuading the Eastman Kodak Company to contribute $1 million toward the renovation of the East Wing of Olin Hall. But most important, he was a friend and advisor to generations of students.

Dean William B. Streett remembers that Scheele's office door "was always open, and whenever I passed by there were one or two undergraduates inside, and often another waiting in the hall, to discuss courses, academic and intellectual interests, and career plans." He was an enthusiastic supporter of the Engineering Co-op Program, and a good-natured participant in informal student-faculty sporting events. Once a year he and his wife Carol would invite the entire chemical engineering Co-op class to a sit-down dinner in their home.



Scheele served on the Common Curriculum Governing Board and the Faculty Council of Representatives, as well as many other committees. He was especially interested in undergraduate education and unusually well-informed on the life and governance of the university. When Cornell president Frank H. T. Rhodes needed someone to negotiate with student activists who had taken over a campus building, he chose Scheele, who carried out the mission with "fairness, strength, and grace."

A fellow of the American Institute of Chemical Engineers, Scheele had received his undergraduate degree from Princeton University (whose athletic endeavors he enthusiastically supported), and his doctorate from the University of Illinois. He is survived by his wife, his mother, a sister, and two nieces.

Contributions may be made to the George F. Scheele Memorial Fund, which has been established by the School of Chemical Engineering.

■ Three faculty members have recently been elected to the National Academy of Engineering. They are ***Sidney Leibovich*** of the Sibley School of Mechanical and Aerospace Engineering, ***Thomas D. O'Rourke*** of the School of Civil and Environmental Engineering, and ***Watt W. Webb*** of the School of Applied and Engineering Physics.

Sidney Leibovich, who holds the Samuel B. Eckert professorship, is a specialist in the physics of strongly swirling flows. His research is relevant to the aerodynamics of aircraft and automobiles, combustion chambers, and natural flows such as tornadoes. He received his doctorate from Cornell in 1965, and came back to join the faculty after a postdoctoral fellowship in mathematics at the University of London. He is a member of the graduate Fields of Applied Mathematics, Theoretical and Applied Mechanics, Mechanical Engineering, and Aerospace Engineering.

Thomas D. O'Rourke's research focuses on the behavior of soil and rock in relation to foundations, tunnels, and buried pipelines. He is particularly concerned with the response of underground infrastructure during earthquakes. He was a member of the official team that investigated the Armenian earthquake in 1988, and he played a key role in the geotechnical reconnaissance of the Loma Prieta, California, earthquake in 1989. He received his doctorate from the University

Liebovich

O'Rourke

Webb

of Illinois at Urbana in 1975 and joined the faculty at Cornell (where he had been an undergraduate) in 1978.

Watt W. Webb uses modern physical optics to study biophysical processes in living cells. Much of his work involves developing new instruments that can probe the intimate functions of individual cells with delicacy and precision. Educated at the Massachusetts Institute of Technology (Sc.D. 1955), he worked at the Union Carbide Metals Company before coming to Cornell in 1961. He is active in several Cornell programs and directs the Developmental Resource for Biophysical Imaging Opto-electronics. He was a founding fellow of the American Institute of Medical and Biological Engineering.

■ Three other faculty members have been elected to fellowship in professional societies. ***Wilfried H. Brutsaert*** of the School of Civil and Environmental Engineering was made a fellow of the American Meteorological Society. ***Donald T. Farley*** of the School of Electrical Engineering was named a fellow of the Institute of Electrical and Electronics Engineers. And ***Robert K. Finn*** of the School of Chemical Engineering was named a fellow of the American Institute of Medical and Biological Engineering.

Others won awards recognizing their professional contributions. ***Philip Holmes*** of the Department of Theoretical and Applied Mechanics won a 1993 Guggenheim fellowship for his paper, "Low-dimensional models of turbulence." ***George S. Kiersch***, an emeritus member of the Department of Geological Sciences, was honored with the Edward B. Burwell Memorial Award, presented by the Geological Society of America. ***Leigh S. Phoenix*** of the Department of Theoretical and Applied Mechanics received the 1992 Harold DeWitt Smith Award from the American Society for Testing and Materials. ***Arthur L. Ruoff*** of the Department of Materials Science and Engineering won the 1993 Bridgman Award from the International Association for High Pressure Science and Technology.

Alex Gaeta of the School of Applied and Engineering Physics and ***Ronitt Rubinfeld*** of the Department of Computer Science were selected as Office of Naval Research Young Investigators. ***Ronald E. Pitt*** of the Department of Agricultural and Biological Engineering received the 1992 Ford New Holland Young Researcher Award from the American Society of Agricultural Engineers.

FACULTY PUBLICATIONS

Current reserch activities in the Cornell College of Engineering are represented by the following publications and conference papers that appeared or were presented during the three-month period October through December 1992. (Earlier entries omitted from previous Quarterly *listings are included here with the year of publication in parentheses.) The names of Cornell personnel are in italics.*

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Aneshansley, D. J., and *R. C. Gorewit*. 1992. Cow sensitivity to electricity during milking. *Journal of Dairy Science* 75:2733–41.

Bell, J. L., and *T. S. Steenhuis*. 1992. Fast and far-reaching flow in soil. Paper read at 84th Annual Meeting, American Society of Agronomy, 1–6 November 1992, in Minneapolis, MN. (*Agronomy Abstracts*, p. 32.)

Gebremedhin, K. G., *J. A. Bartsch*, and *M. C. Jorgensen*. (1992). Predicting roof diaphragm and endwall stiffness from full-scale test results of a metal-clad, post-frame building. *Transactions of the ASAE* 35(3):977–85.

Gebremedhin, K. G., H. B. Manbeck, and E. L. Bahler. 1992. Diaphragm analysis and design of post-frame buildings. In *Post-frame building design*, ed. J. N. Walker and F. E. Woeste, pp. 358. St. Joseph, MI: American Society of Agricultural Engineers.

Gorewit, I. C., *D. J. Aneshansley*, and *L. R. Price*. 1992. Effects of voltages on cows over a complete lactation. 1. Milk production and composition; 2. Health and reproduction. *Journal of Dairy Science* 75:2719–25, 2726–32.

Gupta, R., and *K. G. Gebremedhin*. 1992. Resistance distributions of a metal-plate-connected wood truss. *Forest Products Journal* 42(7/8):11–16.

Gupta, R., *K. G. Gebremedhin*, and *J. R. Cooke*. (1992). Analysis of metal-plate-connected wood trusses with semi-rigid joints. *Transactions of the ASAE* 35(3): 1011–18.

Gupta, R., *K. G. Gebremedhin*, and *M. D. Grigoriu*. 1992. Characterizing the strength of wood truss joints. *Transactions of the ASAE* 35(4):1286–90.

Nektarios, P. A., *T. S. Steenhuis*, and *M. Petrovic*. 1992. Contamination hazard of chemical flow from cultivation of sandy turfgrass sites. Paper read at 84th Annual Meeting, American Society of Agronomy, 1–6 November 1992, in Minneapolis, MN. (*Agronomy Abstracts*, p. 224.)

Pannabecker, T. L., *D. J. Aneshansley*, and *K. W. Beyenbach*. 1992. Unique elctrophysiological effects of dinitrophenol in malpighian tubules. *American Journal of Physiology* 263(3):R607–14

Parlange, J.-Y., *T. S. Steenhuis*, C. Fuentes, and R. Haverkamp. 1992. Soil properties:Measurements and constraints. Paper read at American Geophysical Union Fall Meeting, 7–11 December 1992, in San Francisco, CA. Abstract in *EOS* 73(43, suppl.):204.

Pivetz, B. E., *J. W. Kelsey*, *T. S. Steenhuis*, and *M. Alexander*. 1992. Fast lane (bacterial) life . Paper read at 84th Annual Meeting, American Society of Agronomy, 1–6 November 1992, in Minneapolis, MN. (*Agronomy Abstracts*, p. 53.)

Scott, C. A., and *M. F. Walter*. 1992. Local knowledge and conventional soil science approaches to erosional processes in the Shivalik Himalaya. *Mountain Research and Development* 13(1):61–72.

Shalit, G., *T. S. Steenhuis*, *J. Boll*, *L. D. Geohring*, *H. A. M. Hakvoort*, and *H. Van Es*. 1992. Solute concentration prediction in agricultural drainage lines under structured soil. Paper read at 6th International Drainage Symposium, 13–15 December 1992, in Nashville, TN.

Steenhuis, T. S., *J. Boll*, *I. Merwin*, *J. Selker*, and *S. Saul*. 1992. Wick, zero tension, and other solute samplers evaluated for two soils. Paper read at 84th Annual Meeting, American Society of Agronomy, 1–6 November 1992, in Minneapolis, MN. (*Agronomy Abstracts*, p. 228.)

Steenhuis, T. S., *S. Rice*, *J. Boll*, *I. Merwin*, and *J. Selker*. 1992. Solute samplers for the vadose zone. Paper read at American Geophysical Union Fall Meeting, 7–11 December 1992, in San Francisco, CA. Abstract in *EOS* 73(43, suppl.):209.

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