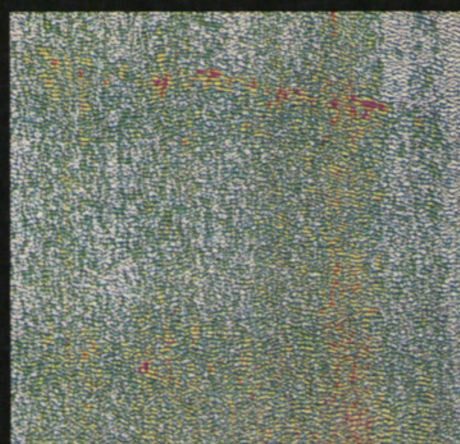
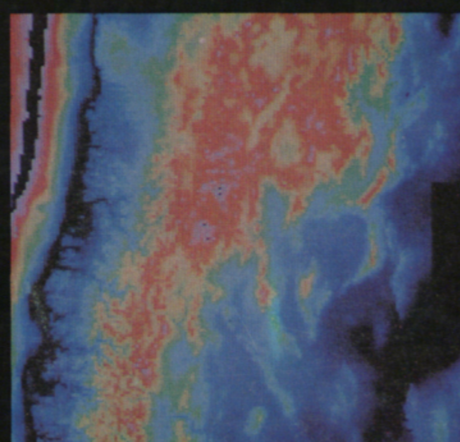
ENGINEERING

CORNELL QUARTERLY





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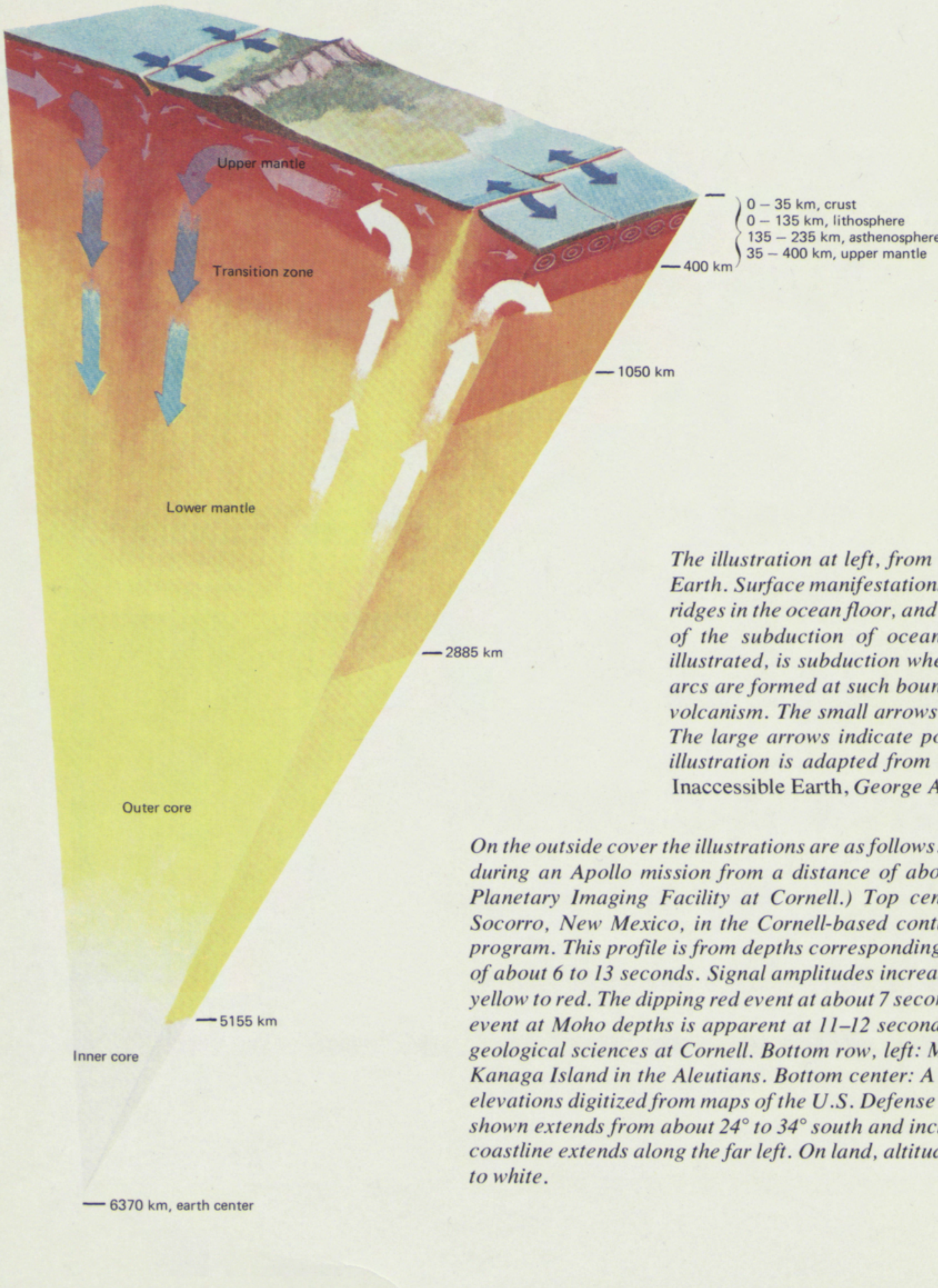
GEOLOGY
AT CORNELL:
ON THE MOVE



The illustration at left, from NASA, represents geologic features of Earth. Surface manifestations of plate tectonics include trenches and ridges in the ocean floor, and mountains generated as a consequence of the subduction of oceanic lithosphere. Another process, not illustrated, is subduction where two oceanic plates converge; island arcs are formed at such boundaries as a result of the accompanying volcanism. The small arrows indicate the motion of the lithosphere. The large arrows indicate possible convection in the mantle. (This illustration is adapted from G. C. Brown and A. E. Mussett, The Inaccessible Earth, *George Allen and Unwin, 1981.)*

On the outside cover the illustrations are as follows. Top row, left: A view of Earth obtained during an Apollo mission from a distance of about 25,000 miles. (Courtesy Spacecraft Planetary Imaging Facility at Cornell.) Top center: A seismic section obtained near Socorro, New Mexico, in the Cornell-based continental reflection profiling (COCORP) program. This profile is from depths corresponding to two-way travel times for the signals of about 6 to 13 seconds. Signal amplitudes increase from white through blue, green, and yellow to red. The dipping red event at about 7 seconds indicates a magma body; a complex event at Moho depths is apparent at 11–12 seconds. Top right: Snee Hall, new home for geological sciences at Cornell. Bottom row, left: Members of a Cornell research team on Kanaga Island in the Aleutians. Bottom center: A color image of Andes topography with elevations digitized from maps of the U.S. Defense Mapping Agency. The geographic area shown extends from about 24° to 34° south and includes parts of Argentina and Chile; the coastline extends along the far left. On land, altitude increases from dark blue through red to white.

IN THIS ISSUE

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THE ASCENDENCY OF THE GEOLOGICAL SCIENCES

by Frank H. T. Rhodes

With a campus framed by spectacular gorges and other glacial legacies, Cornell was from the beginning an obvious place for a strong program in the geological sciences.

Its first professor of geology was the brilliant Charles F. Hartt, who had served as geologist on Agassiz's expedition to Brazil in 1865-66 and who, in 1870, organized the first Cornell expedition there. Hartt proved more interested in Brazilian geology than in that of the Finger Lakes, however, and after his departure in 1874 to head Brazil's Geological Survey, the department was reformed.

Elementary lectures and laboratory instruction were replaced in 1874 by "... critical observation of specimens . . . without the consultation of books." Only after the student had done his own careful study was he permitted to compare his results with those of a master. Although the new approach was not entirely successful, by the early 1890s the department was again prospering, with a major emphasis on paleontology under Henry S. Williams.

With Williams's departure for Yale in 1892, leadership of the department fell to Ralph S. Tarr, who brought physical geography and glacial geology to Cornell for the first time. Among Tarr's major undertakings was an expedition to study the Greenland ice sheet. Incidentally, his party named a glacier there in honor of Cornell.

Field trips to areas of geological interest, introduced by Hartt as early as 1873, were also an important part of Cornell's geology curriculum in the early 1900s. By 1910, with the invention of the automobile truck, excursions as far afield as Watkins Glen could be completed in one day.

Throughout the first half of the twentieth century, the department focused its research and teaching primarily on four areas within the geological sciences: economic geology, mineralogy, paleontology and stratigraphy, and glacial geology and geomorphology. Several courses also stressed engineering applications of geology.

Geology became more closely allied with the physical sciences in the 1960s, and expanded to include geophysics in addition to the strong offerings in mineral resources, geochemistry, and engineering applications. Although only a few federal and state agencies were supporting land-based geology in the 1960s, Cornell received several such grants, along with equipment grants and student fellowships.

The geological sciences, as both a subject of scientific inquiry and a component of liberal learning, have achieved new significance at Cornell and elsewhere during the past fifteen years. No longer confined to the mapping of local areas, no longer merely descriptive of stratigraphic sections and surface features, the earth sciences have given the scientific world a powerful new paradigm in the elegant and daring theory of plate tectonics.

Jack Oliver, who became chairman of the Department of Geological Sciences at Cornell in 1971, recognized the importance of plate tectonics as a powerful concept in unifying previously isolated phenomena—from the physical features of the crust to changing magnetic fields; from continental margins to the structure of the earth's interior. Himself a pioneer, with Bryan Isacks, in relating world-wide distribution of seismicity to plate tectonics, Oliver brought to Cornell a number of scientists, including Isacks, who were noted for their elaborations and applications of the theory. Within a decade, the department grew from four faculty members, eight graduate students, two upperclass majors, and virtually no external research grants or research staff, to fifteen faculty members, fifty-eight graduate students, forty-two upperclass majors, two senior research associates, seven research associates, three postdoctoral associates, and an annual research budget of some $3.9 million distributed among thirty-two separate grants.

This growth and development has continued under the leadership of the current chairman, Donald Turcotte, and reaches a climax in the official opening of Snee Hall. A magnificent new building at the Collegetown entrance to the campus, Snee Hall has been designed especially for the research and teaching needs of the Department of Geological Sciences.

CORNELL UNIVERSITY DEPARTMENT OF GEOLOGICAL SCIENCES

Faculty Members and Research Associates and Their Fields of Interest

Richard W. Allmendinger, Assistant Professor: *foreland contractional deformation*

Muawia Barazangi, Senior Research Associate: *earthquake seismology, seismotectonics*

William A. Bassett, Professor: *optical microscopy; x-ray diffraction; light absorption; light scattering and electrical resistance at high pressures and temperatures, studied through laser heating in diamond cells*

John M. Bird, Professor: *geotectonics, plate tectonics, orogeny, economic geology, ophiolites, origin of terrestrial metals, geology of the Appalachians, paleostress indicators*

Arthur L. Bloom, Professor: *geomorphology, Quaternary tectonics and sea-level changes, Holocene sea-level changes, coastal geomorphology, glacial geomorphology and stratigraphy, denudation rates, planetary surfaces*

Larry D. Brown, Associate Professor: *exploration seismology, deep structure of continental crust, recent crustal movements, digital signal processing, computer graphics*

John L. Cisne, Associate Professor: *invertebrate paleontology, population and community paleoecology, biostratigraphy*

Allan K. Gibbs, Assistant Professor: *economic geology, Precambrian geology*

Bryan L. Isacks, Professor: *seismology and tectonics*

Teresa E. Jordan, Assistant Professor: *tectonic and mechanical behavior of continental crust*

Daniel E. Karig, Professor: *marine geology and geophysics, structural geology of orogenic belts, marginal basins, geomechanics*

Sidney Kaufman, Acting Professor: *exploration geophysics, structure of the deep crust and upper mantle, geothermal resource development*

Robert W. Kay, Associate Professor: *petrology, geochemistry, application of trace-element and isotope geochemistry to the petrogenesis of igneous rocks*

Suzanne Mahlburg Kay, Senior Research Associate: *formation and evolution of the lower continental crust; geochemistry and petrology of convergent margin magmas*

Douglas Nelson, Research Associate: *deep structures of continental crust*

Jack E. Oliver, Professor: *geophysics, seismology, geotectonics, recent vertical movements, deep-crustal reflection studies*

Frank H. T. Rhodes, Professor: *invertebrate paleontology, stratigraphy, history and philosophy of geology, conodont biostratigraphy*

William B. Travers, Associate Professor: *structural geology, tectonics, petroleum geology*

Donald L. Turcotte, Professor: *geophysics, geomechanics, mantle convection, convection in porous media*

Maura Weathers, Senior Research Associate: *structural geology, electron microscopy, microstructures*

Toasting the future Snee Hall at the ground-breaking festivities in October, 1982, were (left to right) Katherine Snee, President Rhodes, Mrs. Rhodes, and William A. Bassett and John M. Bird of the Department of Geological Sciences.

Yet it is not only for the researcher that the geological sciences have gained importance over the past decade and a half. They have assumed new significance in the education of nonscientists as well. The new ascendency of the geological sciences in general education began, perhaps, with those unforgettable photographs of Planet Earth as seen for the first time through the eye of an orbiting spacecraft. That small globe—brown and white, green and blue, solid yet so very fragile—was at once awe-inspiring and humbling. And the new reverence for the home planet engendered by those photographs may be the greatest single benefit to derive from our massive space exploration effort.

What was awakened by those first photographs was reinforced by the Arab oil embargo. Long lines at gas stations brought home, as never before, the finiteness of Earth's resources, and the geological sciences gained new prominence in the intelligent exploitation and wise stewardship of those resources upon which human civilization as we know it depends.

But the value of the geological sciences transcends even their profound influence on our material well-being, for through them we are brought face to face with some of life's most insistent questions, including, for example, questions about the nature of time, our human origins, the origins of our planet and solar system, and the significance of continuity and change.

Some five thousand years ago, Job was advised to "speak to the earth and it shall teach thee." So, too, for students today, whether their aim is to become professional geological scientists or simply well-informed citizens, study in the geological sciences can be among the most exciting and rewarding parts of a university education.

That is why the dedication of Snee Hall is an occasion of such significance, not only for those in Geological Sciences, but for all Cornellians.

Frank H. T. Rhodes is president of Cornell University and professor of geological sciences.

He was educated at the University of Birmingham, England; he received the B.Sc. degree with first-class honors in 1948 and the Ph.D. in 1950. After serving as a postdoctoral fellow and Fulbright scholar at the University of Illinois, he taught at the University of Durham, the University of Illinois, the University of Wales at Swansea, and the University of Michigan. At Michigan he served as chairman of the Department of Geology and Mineralogy and director of the Museum of Paleontology, and became dean of the College of Literature, Science, and the Arts, and then vice-president for academic affairs. He assumed his position at Cornell in 1974.

Recognition he has received for his work in geology includes the Bigsby Medal of the Geological Society of London (1967) and selection as director of the first International Field Studies Conference of the National Science Foundation and the American Geological Institute (1964). He has been active in professional organizations and has published numerous papers and written or edited eleven books and monographs.

SNEE HALL

Big, Beautiful, Friendly, Functional

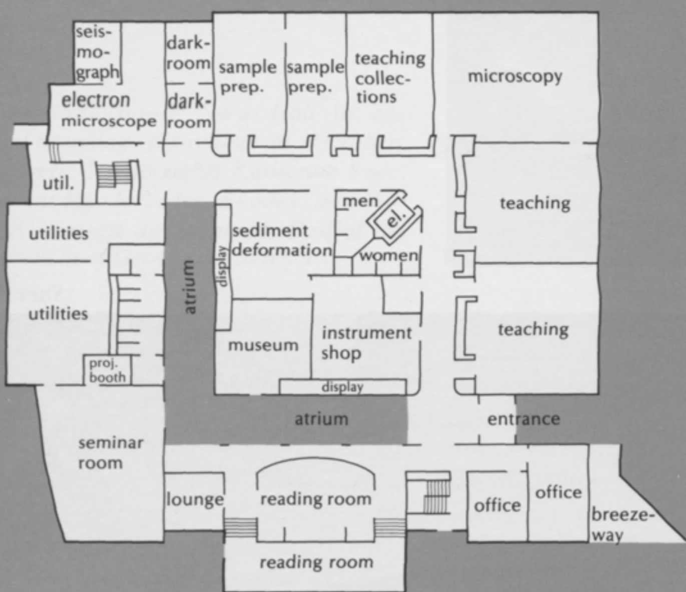
In just two years, Snee Hall has progressed from the twinkle in an architect's eye to the jewel of the engineering quadrangle. Ever since the gray October day in 1982 when ground was broken (*Engineering: Cornell Quarterly* 18(1/2):54-55), passers-by have watched as the building took shape beneath towering cranes. Now the imposing structure that swells into the curve of the road just inside the Collegetown entrance to the campus suggests the importance of geology in the late twentieth century.

By giving the Department of Geological Sciences space of its own, outfitted with up-to-date equipment, Snee Hall will greatly increase research capabilities and enhance the quality of instruction.

Of particular importance are the computational facilities, which have been designed into the building. The main computer, which was crammed into a cubbyhole in Kimball Hall, will now have adequate space. Terminals can be in every faculty office and laboratory, as well as in two terminal rooms for the use of students.

Snee Hall

Level 1



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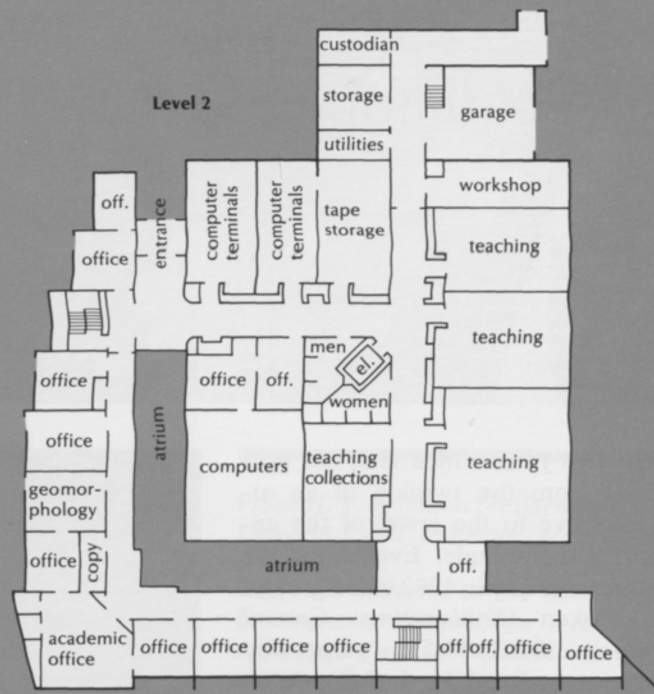

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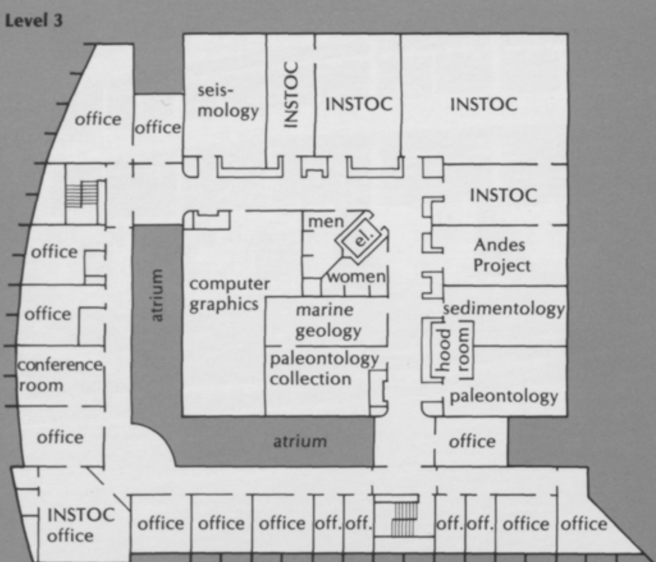

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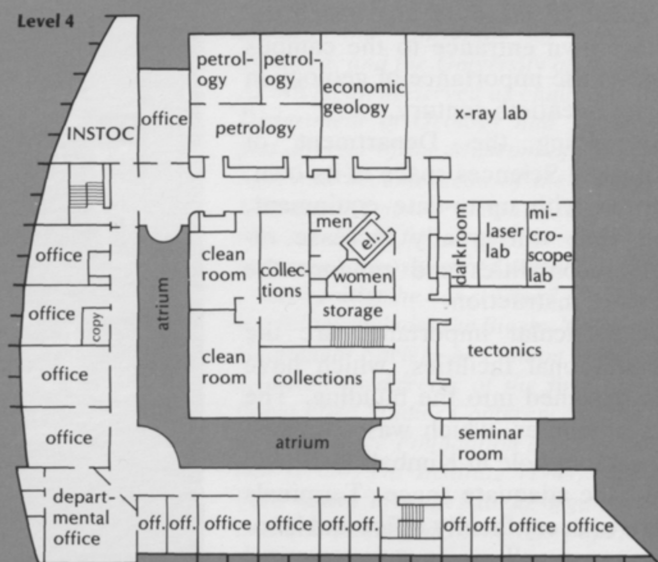


Facing page: Floor plans of Snee Hall show how the L-shaped atrium rises through the building.

Left: Speakers at the ground-breaking ceremony held on October 21, 1982, included Thomas E. Everhart, who was then the dean of the College of Engineering.

Below: During construction, a crane moves material from the deposit behind Thurston Hall to the site on Central Avenue next to Hollister Hall.

The computing capability is important for many projects, but particularly for the processing of seismic reflection profiles. Naturally occurring seismic activity will also be recorded with greater precision, for a new seismic vault has been built, and new equipment is being installed.

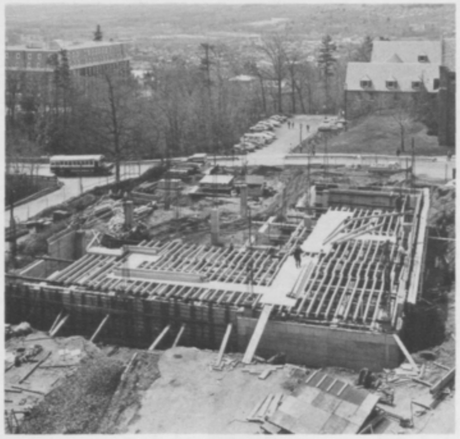
A "clean room," where dust is filtered out of the air so that trace elements and isotopes can be analyzed without danger of contamination, will be especially useful for petrology and geochemistry. Such a facility would have been almost impossible to create in an older building.

A new laboratory is devoted to geomechanics, and there is more space for studies in paleontology, sedimentology, geomorphology, mineralogy, economic geology, and structural geology. An ongoing study of the rocks that underlie the Andes Range will now have a room in which to develop. Another important line of research, which involves tectonic processes on the ocean floor and other aspects of marine geology, will also have a room of its own.

New hoods will facilitate chemical treatments. Special equipment for studying the deformation of rocks is being installed. Facilities for optical microscopy, x-ray diffraction, and laser heating will all be available in the same building; no longer will it be necessary to take samples to different parts of the campus for each analytical technique. The department hopes that in the near future finances will also permit the acquisition of an electron microscope for extremely-high-resolution analysis.

A garage area can be used to outfit trucks with seismic equipment, and there are shops for electronics, sample preparation, and woodworking.

Many features of the new building should contribute to expanded course offerings and innovative teaching. Several seminar and conference rooms replace the two rooms that, in recent years, have been used for classes, exams, seminars, interviews, and faculty meetings. Storage space close to classrooms and good preparation rooms will make it possible to prepare a wider range of material for classroom



use. A video system will greatly facilitate the teaching of microscopy. And a large reading room, supplied with current journals, will provide a comfortable place for students to study.

The Institute for the Study of the Continents (INSTOC), which is responsible for administering the ongoing research program of the Consortium for Continental Reflection Profiling (COCORP), will occupy space in the new building. INSTOC will have an office and a conference room on the third floor, as well as work rooms on other floors.

The overall design of the building is aimed at bringing people together in a comfortable and stimulating environment. The L-shaped atrium, which rises through the building, provides a focal point common to all four floors. The bottom floor of the atrium has a seismic readout and a weather station; an adjacent room contains a mineral museum. Display cases were given by the Class of 1929 and Al Podell, '58, who also donated some of the best specimens in the collection. On the second, third, and fourth floors, offices occupy the southwest corner of the space, while laboratories occupy the remainder of the space, across the atrium. This arrangement separates "working space" and "thinking space" both physically and conceptually, while keeping them close enough so that people can easily move back and forth from one to the other.

Above: Snee Hall during construction.

Right: Moving in.

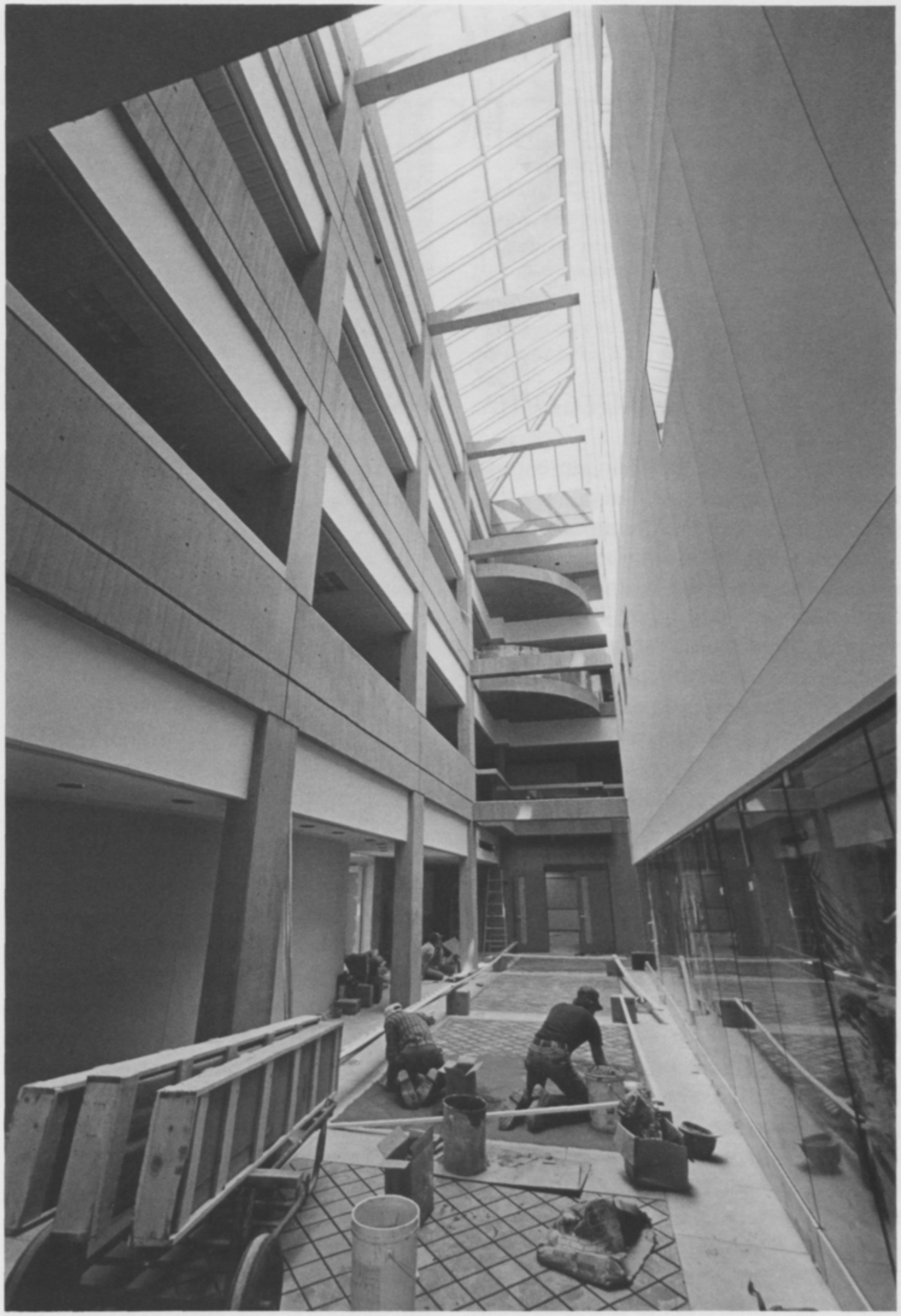
The outside of the building will be graced by new rock parks. The ones that now flank the entrance to Thurston Hall will not be moved, but additional large specimens will be placed at the northwest corner of the building, outside the main entrance, and also to the east. These rock parks are being given by Meyer Bender, '29, and his wife, Gertrude.

During the course of construction, there has been constant communication between the faculty and the architects and builders. As space within the building became real, and it was possible to see characteristics of individual rooms, changes were made in the way they were to be used. As recently as mid-July, a decision was made to use the space right over the computer room for an image-processing facility. This room had been designated for the storage of tapes, but the attractiveness of the room and the relative ease with which connections with the computer can be established make it an ideal place for processing images such as those sent back from satellites.

Several donors have made important contributions to Snee Hall. A major part of the construction cost was financed through the estate of the late William E. Snee, '25 (see *Engineering: Cornell Quarterly* 17(2):38-39); and his wife, Katherine, made further gifts, two of which honor of her nephews, Timothy and Paul Heasley. Significant contributions were made by the Joseph N. Pew, Jr. Charitable Trust, the Leland Fikes Foundation, the Atlantic Richfield Foundation, and the Chevron Fund. George Holbrook, '23, and his wife, Elizabeth Bradley Holbrook, also provided major support.

Moving into the new building was joyful but backbreaking. Sons and daughters of faculty and staff were shanghaied and put to work packing boxes. Most of the actual moving took place during three weeks in the hottest part of August. Items especially difficult to move include the x-ray machines from the top floor of Olin Hall, which are as heavy and cumbersome as pianos, and even more delicate. Equipment that normally runs twenty-four hours a day, such as the computer and the seismograph, had to be disconnected for as short a time as possible.

By the time Cornell opened for the fall semester, the Department of Geological Sciences was in its new home. Much sorting out and filing away still remained to be done, but the fossil dinosaur tracks from the second floor of Kimball Hall were installed in the new atrium, and the faculty was preparing to make an even deeper impression on the history of the earth sciences.—D.P.



ENGINEERING AND THE GEOLOGICAL SCIENCES

by Donald L. Turcotte

I am often asked how an aerospace engineer became chairman of a leading geology department at a major university. On a personal level, the answer involves two accidental meetings, the first with Ron Oxburgh in 1966 and the second with Jack Oliver in 1970. More broadly, the answer relates to a major change in the direction of the geological sciences that occurred during the late 1960s and early 1970s. Here is the story.

During the 1965-66 academic year, I was on sabbatical leave from Cornell's Graduate School of Aerospace Engineering, working on plasma fluid dynamics at the Department of Engineering Science of the University of Oxford. Ron Oxburgh had just joined the geology faculty at Oxford after receiving his Ph.D. under Harry Hess at Princeton. Hess was one of the few geologists in the United States who accepted the hypothesis of "continental drift," with its implications that several hundred million years ago, the Americas were attached to Europe and Africa and the Atlantic Ocean did not exist. Most members of the American geological community regarded continental drift as a fantasy. At Oxford Ron sought a colleague in engineering who could work with him to develop a quantitative theory for continental drift. As a visitor with few commitments, I was asked to fill this role. Although I had no background or prior interest in geology, I found the concept of continental drift fascinating.

A THEORY TO EXPLAIN CONTINENTAL DRIFT

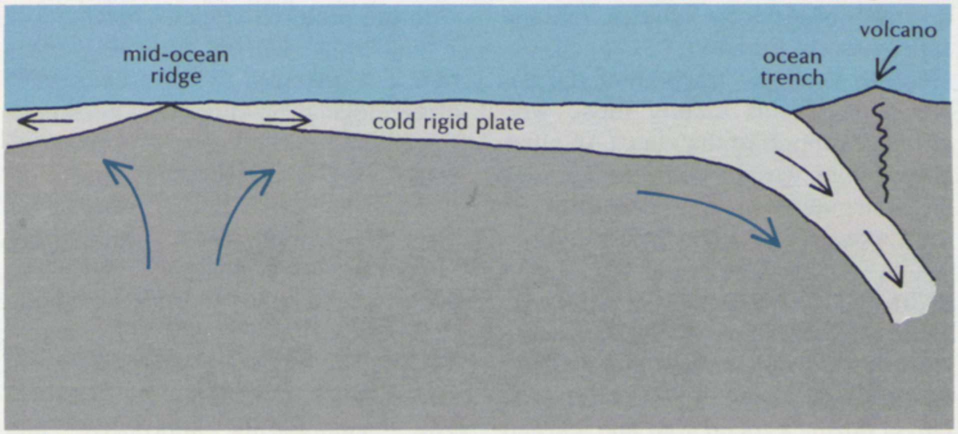
During that year, Ron and I developed a boundary-layer theory for mantle convection that quantitatively explained continental drift. We treated the earth's upper mantle as a fluid layer that is heated from below. A hot thermal boundary layer develops on the lower boundary and a cold thermal boundary layer on the upper boundary, as illustrated in Figure 1b. The boundary layers are unstable and form vertical plumes. The gravitational buoyancy forces drive the flow. We associated the ascending flow with the mid-ocean ridges and the descending flow with ocean trenches, as shown in Figure 1a. We also calculated velocities of drift and values for the surface heat flow that were in agreement with observations.

This work was one aspect of the plate-tectonic revolution, which was based on the hypothesis that the surface of the earth is broken up into a number of rigid plates in relative motion with respect to each other and that earthquakes, volcanism, and mountain building are largely confined to the boundaries between plates. The plates are the cold thermal boundary layers of mantle convection cells.

The decay of the radioactive isotopes of uranium, thorium, and potassium heat the earth's mantle. Because of solid-state creep processes, the mantle behaves as a fluid on geological time scales. Thermal convection converts heat into motion. This motion drives continental drift. The energy associated with earthquakes, volcanic eruptions, and mountain-building represent about 0.1 percent of the available heat energy. The earth is a thermodynamic engine.

The period between 1968 and 1970

Figure 1a



1b

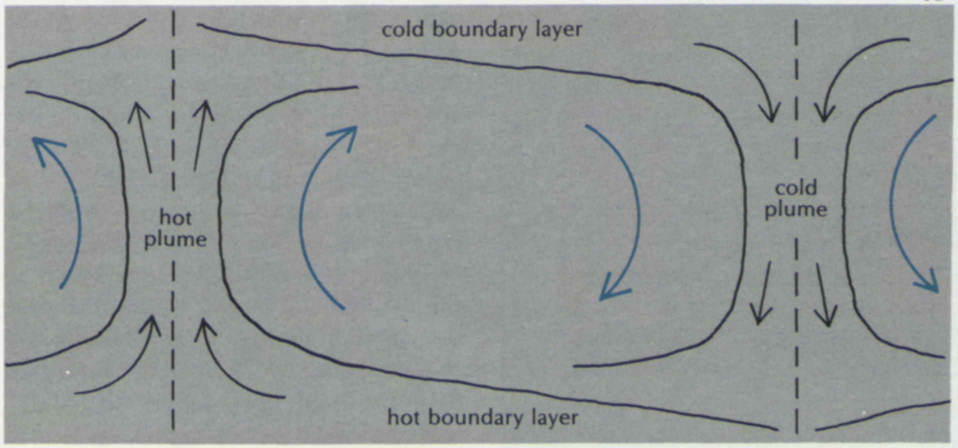


Figure 1. A schematic diagram illustrating a boundary-layer theory for mantle convection. Developed by Turcotte and Oxburgh, the theory provides an explanation for continental drift. The sketch in a *shows the association between ascending flow and ridges in the oceanic floor, and between descending flow and the formation of trenches. The sketch in* b *shows the treatment of the upper mantle as a fluid layer heated from below.*

was a time of great excitement in the earth sciences. Continental drift changed from scientific heresy to a scientific dogma. I was fortunate to be at the right place at the right time to be able to apply my engineering background to exciting new problems concerning how the earth works. The collaboration with Ron Oxburgh led to some twenty-five papers on a variety of subjects: the origin of volcanism, the thermal structure of the crust and mantle, the thermal structure of the moon.

Subsequently, Ron became a member of the Royal Society, professor and head of the earth sciences department at Cambridge University, and president of Queens College, Cambridge. He is also a featured speaker at the dedication of Snee Hall.

Shortly after beginning the collaboration with Ron Oxburgh, I began cooperative work with Ken Torrance, a professor in Cornell's Sibley School of Mechanical Engineering (now Mechanical and Aerospace Engineering), and with Jerry Schubert, a former student of mine who is a professor of earth and planetary sciences at UCLA. Ken and I worked with a number of graduate students to carry out numerical calculations of the structure of mantle convection flows, and we made a series of studies of fundamental processes in geothermal reservoirs. Jerry and I worked on a variety of problems and recently coauthored the first textbook in this area (D. L. Turcotte and G. Schubert, *Geodynamics–Applications of Continuum Physics to Geological Problems*, John Wiley and Sons, New York, 1982).

Despite my interest in mantle convection and related problems, it is likely that I would still be on the faculty of the Sibley School of Mechanical and Aerospace Engineering if the geology department had not become part of the College of Engineering (while retaining its academic ties to the College of Arts and Sciences). During the late 1960s, financial pressures and other problems led the College of Arts and Sciences to decide to terminate an independent geology department, and the College of Engineering (under the deanship of Andrew Schultz, Jr., and subsequently Edmund T. Cranch) decided to seek the transfer of the department. I was among those who strongly supported the idea. (An alternative plan was to combine geology and astronomy in one department in the College of Arts and Sciences.)

BUILDING A STRENGTHENED DEPARTMENT AT CORNELL

At the spring meeting of the American Geophysical Union in 1970, I met Jack Oliver during a social hour and learned that he might be willing to make a move to Cornell. Jack was then chairman of the geology department at Columbia. On the recommendation of the College of Engineering, an offer was made; Jack accepted and arrived at Cornell in July, 1971.

Over the next decade, Jack built a department of geological sciences that included a number of the original contributors to the plate tectonic hypothesis. Bryan Isacks had worked with Jack at Columbia to discover the descending plates beneath island arcs and to explain how the worldwide distribution of earthquakes could be integrated into the hypothesis. Muawia Barazangi had worked, also at Columbia, on the relation of global seismicity to plate tectonics. Jack Bird had shown how plate tectonics could explain the structure and evolution of mountain belts. Dan Karig had explained the formation of marginal basins such as the Sea of Japan. And Bob Kay had contributed significantly to an explanation of the origin of oceanic crust.

My own entry into the group came in 1972, when the Graduate School of Aerospace Engineering was combined with the Sibley School of Mechanical Engineering. During the reorganization, I transferred to the Department of Geological Sciences and became a "geologist," although my formal education in the subject consisted of a one-quarter introductory course at Caltech. My ability in identifying rocks remains a standing joke in the department.

"The 'engineering approach' has proved to be a vigorous and fruitful way of attacking problems in geology. . ."

THE AFFINITY OF MODERN GEOLOGY AND ENGINEERING

The "engineering approach" has proved to be a vigorous and fruitful way of attacking problems in geology, and geology has been a gold mine for problems of interest to engineering researchers. My colleagues and I, for example, have worked not only on mantle convection and hydrothermal reservoirs, but on problems involving magma migration. (We asked how magma reaches the volcano where it erupts, and we concluded that the process is dominated by magma fracture.) We have also worked on a variety of solid-mechanics problems with geological implications.

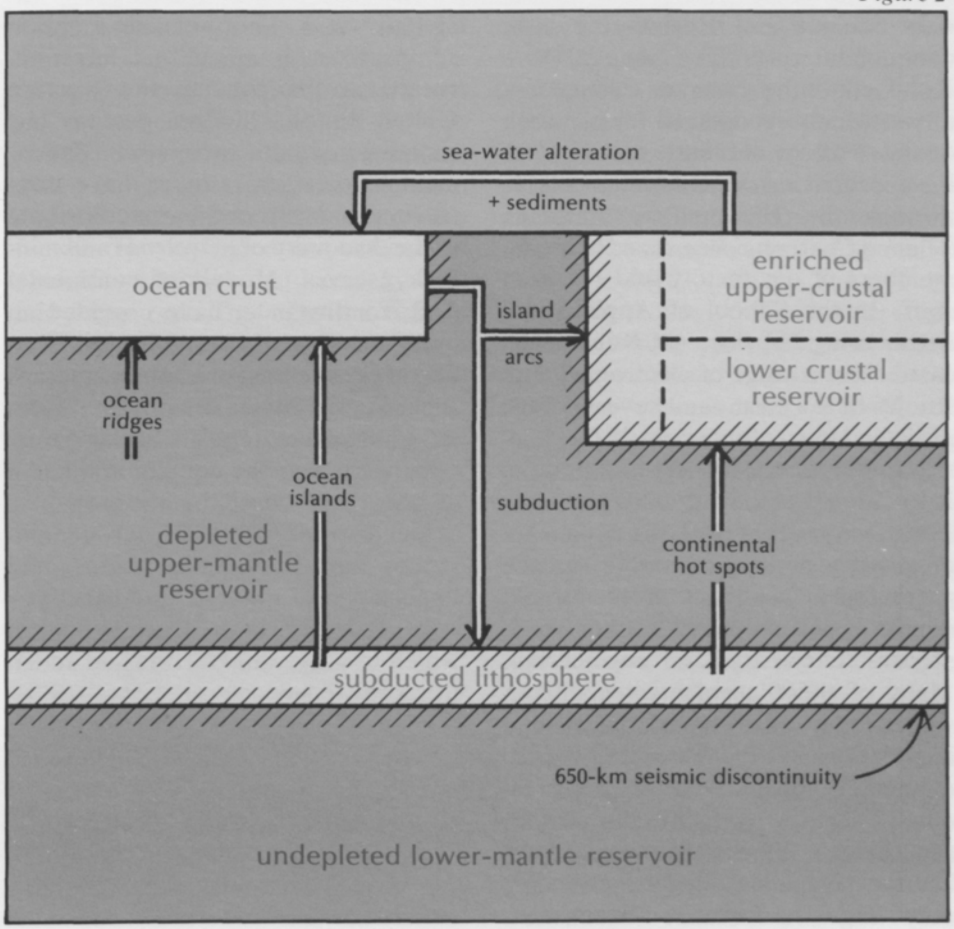
One of our research subjects is the cycle of strain accumulation and release on the San Andreas fault; we carried out a series of finite-element calculations in collaboration with Fred Kulhawy of the School of Civil and Environmental Engineering. Recently, in related work, we have been applying the concept of fractal trees and the renormalization group method to studies of earthquake mechanisms. This work is being carried out in collaboration with Sara Solla, a research associate in the Department of Physics.

Global geochemical cycles is another area of current investigation by our group. This work is being carried out in collaboration with Claude Allègre, director of the Institut de Physik du Glob, Université de Paris. The general concept is illustrated in Figure 2. The continental crust is considered an enriched reservoir that is complementary to the depleted reservoir of the upper mantle. The processes that form continental crust concentrate incompatible elements with large ionic radii; examples are the heat-producing elements uranium and thorium and the rare-earth elements. Isotope systems can be used to study these processes quantitatively. One objective is to find the volume of the continents over the last three billion years by studying isotope ratios in old rocks (see the article in this issue by Bob and Sue Kay).

These activities of mine illustrate how geology can interact with mechanical engineering. Many other examples of the connection between geological sciences and engineering disciplines are found in the University. The search for oil makes the petroleum industry one of the largest users of computers, and similarly, the Consortium for Continental Reflection Profiling (COCORP), which is centered at Cornell, depends heavily on computer capability and has had a number of interactions with people in the School of Electrical Engineering concerning both the hardware and software aspects of data processing. (See Larry Brown's article on COCORP in this issue.) Since rock is a complex material, faculty members in our department and in the Department of Mate-

Figure 2. A possible distribution of chemical reservoirs in the earth, illustrating how material could be transferred between them. According to this model, the 650-kilometer seismic discontinuity acts as a barrier to convection.

Figure 2



rials Science and Engineering have common interests; for example, Dave Kohlstedt of the materials science faculty is widely recognized for his work on the rheology of mantle rocks. Also, the excellent instrumentation available through the University's Materials Science Center has been used by many members of our faculty and research staff. In the School of Applied and Engineering Physics, Art Kuckes has carried out a range of electromagnetic studies of the earth, and several of his projects have complemented the seismic studies of COCORP.

Looking back on the 1970s and early 1980s, we see that the large expansion of geology as a quantitative science presented a wealth of problems and opportunities in applied mathematics, physics, chemistry, and engineering. Many of these problems remain unsolved today. Many have large societal implications. For example, earthquake and volcanic hazards are present in many parts of the world. (Southern California has one of the highest probabilities of experiencing very large earthquakes. Mount St. Helens was a minor volcanic eruption compared with many that have occurred in the past in the western United States.) Modern geology has economic significance also. Fundamental geological studies have contributed and will continue to contribute to the discovery of petroleum and mineral reserves. Models of continental drift, for instance, have provided an understanding of the global distribution of petroleum—of how cold regions such as the North Slope of Alaska have petroleum deposits because they once were near the equator and had a climate that favored organic growth.

Our experience at Cornell demonstrates the wide-ranging interest and importance of modern geological science. It is clearly an exciting field in which to apply engineering and scientific knowledge.

Donald L. Turcotte, a professor of geological sciences, has been chairman of the department since 1981. As he discusses in his article, he began his career in aerospace engineering and moved into the geological sciences through his work on mantle convection. His degrees are the B.S. from the California Institute of Technology (1954), the M.Aero.Eng. from Cornell (1955), and the Ph.D. from Caltech (1958).

Before joining the Cornell faculty in 1959, Turcotte worked as a research engineer at the Jet Propulsion Laboratory in Pasadena, California, and taught at the United States Naval Postgraduate School in Monterrey. Throughout his career, he has served as a consultant to industrial firms and to the army.

He is a fellow of the American Geophysical Union and of the Geological Society of America, and is active in several other professional societies. He serves on a number of committees, panels, and commissions for the National Academy of Sciences, NASA, the International Union of Geodesy and Geophysics, and the American Geophysical Union. In 1981 he was awarded the Day Medal of the Geological Society of America, and in 1982 he was the William Smith Lecturer at the Geological Society of London.

CORNELL GEOLOGY, 1868-1984: A REVIEW

by William R. Brice

The groundwork for Cornell's geology department extends back beyond the opening of the University in the fall of 1868. While the new institution was still being planned, Louis Agassiz, a Harvard professor who was highly regarded as a scientist and lecturer, was offered one of the first nonresident professorships at Cornell. He not only accepted, but made suggestions to Andrew Dixon White, Cornell's first president, and to Ezra Cornell, the University's founder, about the appointment of professors. Agassiz was especially interested in the chair of geology, the discipline he felt was "the most important among the physical sciences." After considering other geologists, the board of trustees made the appointment Agassiz had recommended; in October Ezra Cornell sent Charles Frederick Hartt a telegram that read, "You were elected this morning," and a geology department at Cornell became a reality.

Note: Reminiscences and photographs suitable for inclusion in a full-length history of geology at Cornell are requested by the author, William R. Brice, Department of Geology and Planetary Sciences, University of Pittsburgh, Johnstown, PA 15904. He is especially in need of material from the 1950s and 1960s.

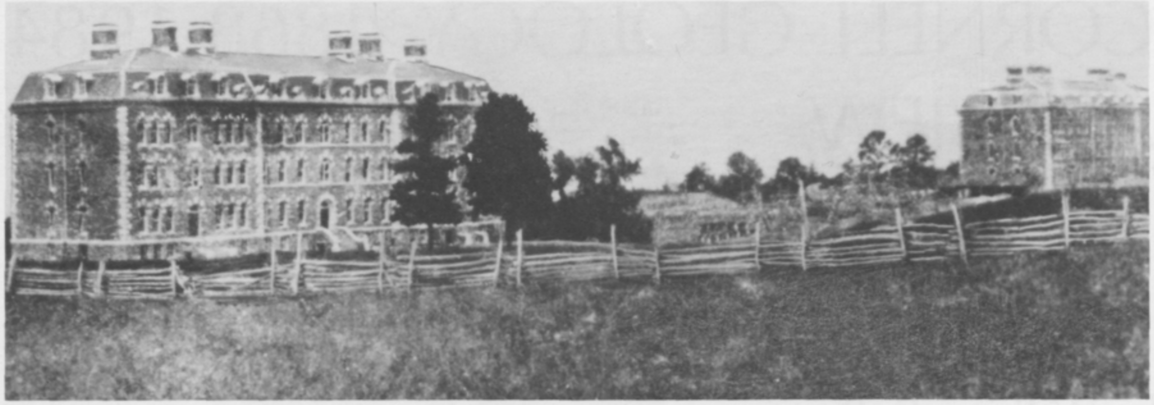
The new geology professor had been a student of Agassiz's for three years, and was one of two geologists on the famous Thayer Expedition to Brazil in 1865-66—a venture that Louis Agassiz had organized. That was the first of many trips Hartt made to Brazil; after he came to Cornell he took several students with him on the expeditions.

At Cornell that first autumn, the campus consisted of two classroom buildings and a few dormitories, connected by very muddy paths. The entering class of 412 students was the largest ever admitted to a new university up to that time; there were twice as many students as could be housed, and the classroom space was adequate for only one-third of them. The geology department was confined to a single room adjoining one of the coal cellars in the southeast corner of South Building—what is now called Morrill Hall. Although some rooms on the second and third floors were used to house geology collections in wall cases, the almost constant presence of classes there forced the students and Hartt to do their work in the basement. McGraw Hall was not completed until much later; geology moved into its South Wing in about 1873.

Hartt

EXPEDITIONS TO BRAZIL IN THE EARLY 1870s

In June of 1870, Hartt and his party set sail from New York on the first of two Cornell geological expeditions to Brazil. The necessary funds were



The Cornell campus as it looked when Hartt arrived at the new university in 1868.

raised from many sources, but the largest amount, $1,000, came from Colonel Edwin B. Morgan, a University trustee from Aurora, New York, and the two trips became known as the Morgan Expeditions. Besides Hartt, the group included Professor Albert N. Prentiss of the botany department and nine students from Hartt's classes.

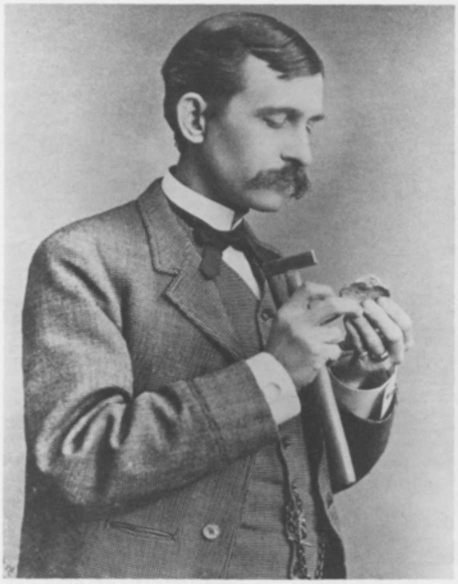
Several of these students became notable figures in geology: Orville A. Derby (B.S. 1873, M.S. 1874) became the chief geologist of Brazil. Theodore B. Comstock (B.S. 1870, D.Sc. 1886) was appointed the first assistant professor of applied geology at Cornell and was put in charge of the department in 1875; eventually he became the president of the University of Arizona. (Comstock's B.S. degree was the first degree in geology awarded by Cornell, and his doctorate was the first and only D.Sc. in geology.) William Stebbins Barnard (B.S. 1871) was later an assistant professor of entomology at Cornell (1879-81), and eventually became a professor of natural history at Drake University. Herbert Hunting Smith (1868-70, no degree) became a member of the Alabama Geological Survey and spent many years in Brazil as a collector for museums. Hartt often spoke in glowing terms of these four, but especially of Derby, who continued the Brazilian work after Hartt's death in 1878. Hartt is quoted as saying that he had made at least one discovery in going to Brazil, and that was Derby.

Derby

The purpose of Hartt's last trip to Brazil, made in 1874, was to attempt to create a formal Brazilian Geologic Survey. He was successful, and the Commissao Geologic do Imperio do Brazil began operations in May of 1875. Hartt was the director and his assistant was a student from Cornell, John Casper Branner (B.S. 1882), who later, in 1913, became president of Stanford University. Hartt soon attracted Derby back to Brazil; except for a few short visits to the United States, Derby remained there until he took his own life in 1915. During his

Comstock

H. S. Williams



Tarr

years in Brazil, Derby continued and expanded the work begun by Hartt and between them they literally put Brazilian geology on the map. Even today, several of the geology faculty members and their students are continuing the Cornell concern with South American geology.

THE EARLY YEARS WITH COMSTOCK AND WILLIAMS

When Derby, who had been the instructor during Hartt's absence, left Cornell in 1875, the department was put in the care of Comstock, and a new instructor of zoology and paleontology, Frederic W. Simonds (who later had a distinguished career at the University of Texas in economic geology) joined the faculty. The following year, Comstock taught the first summer classes ever offered at Cornell; the official Cornell Summer School did not get underway until 1892. In addition, Comstock organized geology courses for students in both architecture and engineering, courses that were among the first of their kind in the country.

In 1879 Comstock tried to force a promotion by threatening to resign, which the trustees allowed him to do. The department was taken over by two men well known in the Ithaca community: Samuel Gardner Williams, a former principal of Ithaca Academy, and Henry Shaler Williams, who had worked with his family business in Ithaca for several years after completing his degrees at Yale. (The two men were not related). Samuel Gardner Williams was a dynamic teacher, well acquainted with secondary schools, and eventually, in 1886, he became the University's first professor of the science and art of teaching. Henry Shaler Williams became head of the geology department and professor of geology and paleontology—a change that was to shape the character and focus of the department for many years to come, for Williams was an excellent paleontologist. Hartt and Derby had begun the paleontological focus, but Williams developed it, especially through his leadership in studying the local Devonian rocks and his research on carboniferous strata for the limited United States Geological Survey. Largely as a result of Williams' work on the carboniferous rocks, geologists today use the terms *Mississippian* and *Pennsylvanian* instead of *lower* and *upper carboniferous*.

Williams was instrumental also in founding the Society of Sigma Xi and the Geological Society of America. The first formal meeting of the Geological Society was held in Sage Hall on the Cornell campus on December 27, 1888, and Williams was elected treasurer. Of the thirteen members who attended that meeting, six had, or soon would have, a connection with the Cornell geology department. (The Geological Society has returned to its birthplace for a meeting only once, in 1924.)

By 1892 Williams' reputation was such that James D. Dana, his former professor, personally selected him as his successor at Yale, a move that left the Cornell department like a ship without a captain. But in the spring of 1892, a new captain was chosen: Ralph Stockman Tarr.

EXPANSION UNDER TARR TO A FOUR-MAN CADRE

Tarr, a Harvard graduate, was a glacial geologist and physical geographer, and his appointment immediately expanded the department into those areas. In order to maintain instruction in mineralogy (by then this subject was being taught in the geology rather than the chemistry department) and rock study, as well as paleontology, Tarr was able to expand the faculty with the appointment of two new assistant professors in 1894. These were Gilbert D. Harris (Bachelor of Philosophy 1886), who had studied with Henry Shaler Williams, and Adam Capen Gill, who had studied at Amherst and Johns Hopkins and had a fresh Ph. D. in mineralogy from Munich. Four years later Heinrich Ries, an economic geologist, came to complete the cadre that was to dominate the department for the next forty years.

In his attempt to divest himself of responsibility for subjects outside his own particular area of interest, and probably also to avoid as much administrative duty as possible, Tarr organized what were essentially three separate divisions: Dynamic Geology and Physical Geography (Tarr), Paleontology and Stratigraphic Geology (Harris), and Mineralogy and Petrography (Gill). After Ries arrived, a fourth area, Economic Geology, was added, but under Tarr's direction. In essence, no one was "in charge" of the overall department. Each person was allowed to develop his own little fiefdom. This subdivision seems to lie at the heart of the interpersonal animosity and strife that existed in the department for many years afterward.

Before his untimely death in 1912, Tarr led expeditions of Cornellians to Greenland in 1896 and to Yakutat Bay, Alaska, in 1905, 1906, and 1909. He was greatly loved and esteemed by his students; the Tarr Boulder still stands

Above: Members of the 1896 Cornell expedition to Greenland were, left to right: Lawrence Martin, T. L. Watson, Professor Adam C. Gill, E. M. Kindle, Professor Ralph S. Tarr, and J. O. Bonsteel. (Photo courtesy of the Cornell department.)

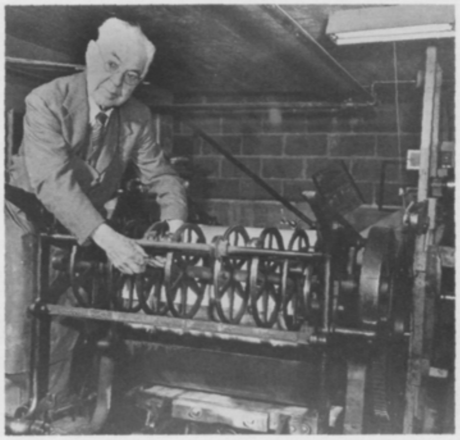
Below: The Ionthina, *photographed at her launching in about 1896, was the first of several motor launches used at Cornell for geology field trips. (Photo courtesy of the Paleontological Research Institution and Professor John W. Wells.)*

at the southwest corner of McGraw Hall as a reminder of their admiration.

One of those admirers, Oskar Dietrich von Engeln, became Tarr's successor. Von Engeln's connection with the department spanned sixty-one years: he entered as a student in 1904 and died an emeritus professor in 1965. During this long span of time, he participated in the Alaskan expeditions with Tarr, but the heart and soul of his geology was the Finger Lakes. His last work, written at the age of eighty-one, was *The Finger Lakes Region: Its Origin and Nature*. He was a popular teacher, especially among the many students who attended his summer classes. From 1944 until 1947, he served as chairman.

PALEONTOLOGY FOR FORTY YEARS UNDER HARRIS

Until the 1930s, Cornell paleontology remained in the hands of Harris, who is well remembered not only for his pioneering work with Tertiary fauna, but for his boats. To enable his students to reach some otherwise inaccessible fossil locations, Harris acquired a succession of launches powered by gasoline engines. The first of these was the paddle-wheel-powered *Ianthina*, which in 1896 and 1897 transported a party from Ithaca to the Miocene beds of Calvert Cliffs along Chesapeake Bay and from there on down to the Carolinas. The second was the *Orthoceras*, named for its slender shape. A third, *Ecphora*, with sleeping accommodations for six, took groups on round-trip excursions to the Chesapeake region in 1914 and 1915; the students on one of these expeditions shipped more than sixty boxes and barrels of samples back to Cornell.



Gilbert D. Harris continued to edit and print paleontological journals for many years after his retirement. He was eighty-four years old when this photograph was taken.

Especially memorable is the Cornell Summer School of Field Geology, which Harris conducted from 1899 to 1909 in the Helderberg Mountains of eastern New York. The *Orthoceras* and the *Ianthina* transported the participants from Ithaca via the Erie Canal to the Helderberg region, with many stops along the way and excursions to Lake Champlain.

In keeping with Cornell's enlightened policy of admitting women, Harris welcomed them; over half the students in his field courses in 1901 were listed either as Miss or Mrs. Unfortunately for the department, it appears that his colleagues did not feel the same way, and as late as the 1930s, other members of the faculty were actively discouraging women from choosing geology (other than paleontology) as a career. (The first female member of the geology faculty above the rank of teaching or research assistant, instructor, or lecturer was Teresa E. Jordan, named an assistant professor in 1984.)

Harris's professional activities included the founding of the *Bulletins of American Paleontology* (octavo) in 1895 and *Paleontographica Americana* (monographs in quarto) in 1917. For many years he printed these publications himself on a press in McGraw Hall.

Harris also served as director of the Louisiana Geologic Survey from 1899 to 1909. He managed this by arranging to teach at Cornell during the fall and summer terms and to work in Louisiana during the winter (allowing him to escape the Ithaca winters).

Harris retired in 1934 after forty-one years at Cornell and from then on devoted his time to the Paleontological Research Institution, which he had founded in 1932. The institution was housed in a little building, just behind his house, that was known affectionately as the "Cabina." Today, from its location on the west side of Cayuga Lake, the institution Harris founded still publishes the journals he started, and continues to encourage and support research in paleontology, the subject to which he devoted his working life.

Women associated with the department around 1927 were (left to right): Katherine Van Winkle Palmer (Ph.D. '25); Marion Burfoot (wife of Professor James D. Burfoot and later department secretary); Ruth St. John (A.B. '23, M.A. '25); Carol Heminway (M.A. '28); Helen Tucker (Ph.D. '37); Elizabeth Baker (A.B. '28, M.A. '30, wife of Professor John W. Wells); Pearl Sheldon (A.B. '08, M.A. '09, Ph.D. '11, assistant 1906-08, 1911-12, and 1914, lecturer 1912-14, curator 1922-30); Georgianna Duncan (M.A. '28). (Photograph courtesy of Benjamin Shaub, M.E. '25, M.S. '28, Ph.D. '29.)

GILL IN MINERALOGY, RIES IN ECONOMIC GEOLOGY

Adam Capen Gill, the other faculty member who arrived with Harris in 1894, is remembered more as a teacher than as a researcher. Former students have described him as "one of the most effective and inspiring of teachers..." and as "a scholar in the truest sense, prizing learning for itself primarily and not for the sake of displaying it."

The fourth member of the group formed in the 1890s, Heinrich Ries, served as chairman from 1914 until 1937. Doc, as he was known to his many students, was an economic geologist with a specialty in clay geology. His first real experience with clay came from a summer job under the direction of eighty-year-old James Hall of the New York survey; he did such excellent work that he soon became "stuck in clay," as he liked to say. But there were other sides to Ries's accomplishment at Cornell. One was his work in engineering geology, initiated by his "inheritance" of a geology course for engineers; he became almost as well known for his teaching of engineering geology as for his work in clay mineralogy. His text, *Engineering Geology,* co-authored with Thomas L. Watson (a Cornell Ph.D. of 1897 who had been on the Tarr Greenland expedition of 1896) went through five editions. Because of Ries's efforts, Cornell had the first laboratory in the country for testing molding sands. He also developed one of the finest collections of ore samples—a collection that has become more valuable over time, since many of the deposits were depleted long ago. Today Cornell students working under Professor Allan Gibbs can study samples from mines that may have closed more than seventy-five years ago.

THE RETURN OF WILLIAMS AS DEPARTMENT HEAD

The administrative situation in the department deteriorated after Henry Shaler Williams returned to Cornell in 1904 as professor of geology, director of the museum, and head of the department. Part of the reason for the move was that Williams and his family wanted to return to their Ithaca home, but there may also have been a desire on the part of the University administration to bring some order to the seeming chaos in McGraw Hall. If there was such a motive, the new organization was only partially successful, for while the areas of Gill, Harris, and Ries came under the direction of Williams, Tarr split off to form the Department of Dynamic Geology and Physical Geography (soon, in 1906, reduced to Physical Geography). In this Tarr had some precedence, for during the early years of the University there was a School of Physical Geography as well as a School of Geology. The split was acknowledged by the trustees, for in the fall of 1906 there were separate line items in the budget appropriations for "Geology" and for "Physical Geography." By 1910, however, there was a budget appropriation only for "Geology (Including Physical Geography, Mineralogy, etc.)." Tarr continued as the head of Physical Geography until his death in 1912, but as far as the administration was concerned, there was only one department and Williams was in charge.

Given the current emphasis on seismology, it is interesting to note that Williams purchased the first seismic equipment for the department in 1907. For several years after that, Pearl Sheldon, an assistant in the department, was in charge of the instrument. Unfortunately, the records, which were traced on a smoked drum, have been lost. What a contrast that equipment would make with the modern devices!

This building served as headquarters of the Henry Shaler Williams field camp at Spruce Creek, Pennsylvania. (Photograph courtesy of George D. Williams, Ph.D. '51.)

NEW FACULTY BLOOD IN THE DEPARTMENT

As the "Old Guard" aged, new men came to Cornell to begin building their own legends. One of these was Charles Merrick Nevin (M.S. 1922, Ph.D. 1925), affectionately known as Chief What-Are-You-Standing-On Nevin. The first structural geologist on the staff, Nevin was chairman from 1939 to 1944, and from 1930 until his retirement he was in charge of the Henry Shaler Williams field camp at Spruce Creek, Pennsylvania. (Professor William Travers currently fills a similar role each summer at the new Sierra Madre field camp in Wyoming.)

Life was rough at Spruce Creek: The "Chief" stayed with the fellows and slept on an air mattress; occasionally the air would mysteriously drain out overnight. The creek was the bath and usually the laundry. Breakfast was often prepared by Nevin, who was not noted as a cook, and everyone was on his own for lunch. The evening meal, however, was the camp's salvation, at least in the post-World War II years, for the whole group went to the home of Mrs. Grapheus for a good dinner and maybe some home-made ice cream. Some former students who camped at Spruce Creek may remember the search for "trap rock" that turned out to be sandstone, or the way the boys cut through the railroad tunnels between trains. They all had their favorite stories of Nevin and the field camp, but few ever beat him at bridge or quoits.

Right: Emeritus Professor Storrs W. Cole, an authority on large forminifera, remains a resident of Ithaca.

Another member who joined the department shortly after Nevin arrived was James Dabney Burfoot (Ph.D. 1929), better known as Dan, who took over the duties in mineralogy from Gill. Burfoot's wife, too, was involved in departmental activities, for she served as the secretary for many years. Then, just before World War II, Alfred Anderson assumed the duties in economic geology. So it was that Nevin, von Engeln, Burfoot, and Anderson, plus various teaching assistants and other graduate students, carried the department through the war years.

After the war, two new teachers came and made lasting impressions on the department: Storrs W. Cole (B.S. 1925, M.S. 1928, Ph.D. 1930) and John W. Wells (M.A. 1930, Ph.D. 1933). Both men have had long and distinguished careers in paleontology, Cole as an expert on large foraminifera and Wells as an authority on corals. (In 1963 Wells discovered that corals can be used as an indicator of the number of days per year in the earth's geologic

Right: John W. Wells, a distinguished paleontologist in the department, retired in 1973 and remains in Ithaca.

Below: A mountain, a river, and a lake are named for Everett P. Wheeler, who was associated with the department for many years as student, researcher, and field geologist.

past; he used fossils to show that the rotational speed of the planet is becoming slower and the days longer.) At Cornell both Cole and Wells continued the long tradition of paleontological and stratigraphic studies that began with Hartt, and Wells continued the study of the local Devonian strata that Williams loved so well. Both were on the scientific team that studied the Bikini atoll prior to and after the atomic bomb tests there, and both served as chairman of the department, Cole from 1947 to 1962 and Wells from 1962 to 1965. Wells was the first member of the geology faculty to be elected to the National Academy of Sciences (he was joined in 1984 by Jack E. Oliver). In 1983 Cole received the Cushman Foundation award in recognition of his work on the larger foraminifera.

LONG CAREERS IN GEOLOGY AT CORNELL

The history of Cornell geology has been shaped in part by the contributions of a number of people, such as Nevin, von Engeln, and Burfoot, who

A time capsule placed in the cornerstone of Deerborn Hall in 1932 was recovered this past summer by historian William Brice (at center) and colleagues. Handing up the contents (mostly fossils selected by contemporary department members and associates) is Peter Hoover, director of the local Paleontological Research Institution. The building originally belonged to Professor Gilbert D. Harris, founder of the research institution, and in recent years has been used by the geological sciences department for storage.

were students in the department and stayed as staff and faculty members for their entire careers.

Another long-standing member who began his Cornell career as a student was Everett Pepperell Wheeler, 2nd (B.S. 1923, M.S. 1926, Ph.D. 1930). Pep, as he was known to his friends, was officially a research associate, although he also did much teaching through his example and his counseling. His major area of study was the anorthosite terrane of Labrador; eventually he mapped some 27,000 square kilometers, often having to make his own topographic maps before he could do the geologic work. Pep, who died in 1974, holds a special place in the hearts of all who knew him, and he is the only member of the department, so far as is known, to have a mountain, a river, and a lake named in his honor.

BEGINNING OF CHANGE IN THE 1960s AND 1970s

A marked change in the department began to occur in the 1960s as more emphasis was placed on areas other than paleontology. Shortly after he began his tenure in 1965, George A. Kiersch emphasized the new character of the department by recommending a name change from the Department of Geology and Geography, as it had become under von Engeln, to the Department of Geological Sciences. Kiersch brought to the department an international reputation in engineering geology, and he continued the tradition of teaching special geology classes for engineers, a practice Comstock had begun in 1875.

Other newcomers included Arthur L. Bloom and Philip M. Orville, who came in 1960 with degrees from Yale (in this move they were following the path of Henry Shaler Williams). Bloom, a current member of the department, continues the work in glacial geology and geomorphology begun by Tarr. Orville introduced geochemistry, and before his return to Yale (another Williams similarity), he began studies in high-pressure and high-temperature phase equilibria. (This is an area in which William A. Bassett is working today, using much greater pressures and temperatures.)

In 1963 Shailer S. Philbrick joined the faculty as a visiting professor after a thirty-year career with the Army Corps of Engineers. In 1966 he became a regular full-time member of the faculty. In addition to teaching advanced courses in hydrology and sedimentation, Philbrick was in charge of the introductory class, Geological Sciences 101; the enrollment grew from 180 in 1965 to 250 in 1968, establishing a modern record that has yet to be surpassed. Among Philbrick's special projects at Cornell was a study to find ways of preserving the American Falls of Niagara.

In 1969 the University administration announced possible changes, including perhaps a dismantling of the entire department, and for the next two years things were in turmoil. Class enrollments declined, and in contrast to the previous steady rise in numbers of students, there was almost a total cessation of applications for graduate school and a precipitous drop in undergraduate majors. Most importantly, faculty morale was undermined. In 1971, after many months of review by the University administration, the department was physically moved to the engineering campus and Jack E. Oliver, appointed the Irving Porter Church professor of engineering, became chairman. With this move the department began a new relationship with the College of Engineering, while maintaining academic ties to the College of Arts and Sciences.

Over the next few years, several new people, all well known for their work in plate tectonics, joined Oliver as the department expanded into the field of geotectonics. These new faculty members were Bryan Isacks in seismology, John M. Bird in tectonics, Daniel E. Karig in marine geology, Robert M. Kay in geochemistry, and Donald L. Turcotte in fluid dynamics.

Soon after the alignment with the College of Engineering, Oliver created the Consortium for Continental Reflection Profiling (COCORP) to carry out a systematic study of deep continental structure. This group has literally opened a new frontier of science and it continues the work with Sidney Kaufman (who came to Cornell after a long and successful career with the Shell Oil Company) as the executive director and Larry D. Brown and Oliver as co-principal investigators. Recently, Oliver expanded the scope of the COCORP idea with the establishment of the Institute for the Study of the Continents (INSTOC). One of the new institute's first activities was to help sponsor the International Symposium on Deep Structure of the Continental Crust, which was held at Cornell in June of 1984.

Despite all the tectonic activity, paleontology has not been overlooked, for that long-standing subject is in the capable hands of John L. Cisne, who joined the staff upon the retirement of Wells in 1973. A bonus was the boost given to paleontology when Frank H. T. Rhodes, well known for his work with fossil conodonts, became president of the University.

The development of the department under Oliver and the current chairman, Turcotte, is strikingly evident in the collection of articles in this issue of *Engineering*. The history of geology at Cornell continues at a rapid pace, accelerated today by the move to a new building with excellent modern facilities, and we look forward to a future as promising as the past has been fruitful.

William R. Brice, associate professor of geology at the University of Pittsburgh at Johnstown, is a Cornell Ph.D. who has taught summer courses in geology at Cornell since 1976. This article is based on a full-length history of geology at Cornell, still in preparation.

Brice received his undergraduate education at the University of Florida, earning the B.S. degree in physics in 1958. After service in the army, he taught in Florida high schools for several years and then went to Tasmania, where he taught high school and studied at the University of Tasmania for the Diploma of Education, granted in 1965. After two more years of high-school teaching in Florida, he entered Cornell and earned the M.S.T. degree (in teaching) in 1968 and the Ph.D. in geochemistry in 1971. Currently he is active in the National Association of Geology Teachers.

Brice says that his interest in the history of geology stems from his experience as a student in the classes of John Wells, now a Cornell professor of geological sciences, emeritus.

GEOLOGY 2020

by Jack Oliver

It is presumptuous, of course, for anyone to forecast the future of a science for thirty-six years, or even one year. Still, scientific researchers planning the most appropriate and effective direction for their efforts are forced to envision the future on the basis of perspectives of the past and the present. Some possible long-term developments in geology are suggested here, with full recognition that a reader of this article in the year 2020, should there by chance be one, will surely suggest that 20/2000 would have been a far better title!

To forecast the future of a science, it is essential to recognize the speed with which modern science develops. Thirty-six years ago, the earth was thought to be 2.5 billion years old, not 4.5 billion as we surmise today. *No* humans, let alone geologists, had been to the tops of the highest mountains, or the depths of the sea, or the moon. Geologists have now been to all of these places. The continents were thought to be fixed, land bridges were said to come and go to permit organisms to cross the seas, and the Pacific basin was a possible birthplace for the moon. Now the continents are thought to drift and thereby provide transportation, and the Pacific is said to be less than 200 million years old, too young for motherhood.

This rapid pace of development of the science seems certain to continue through 2020. Why? How can we be sure the discoveries have not run out? The reason is simply that the earth is by no means fully explored to the level of man's capability. History tells us repeatedly that whenever we explore an unknown region we are initially astonished, but eventually come away with a more profound understanding of the planet, and new benefits for mankind.

EXPLORATION AND MAPPING: KNOWLEDGE IN HAND

It is only in the last few hundred years that humans have come to explore and comprehend the earth in a global sense. Imagine that! The earth has been drifting through space for 4.5 billion years, and humans have occupied it for a few million of those years, but only in the last tiny, tiny fraction of those immense time intervals has any organism known what the entire surface of the earth looks like!

Geographical exploration of the surface was first. The heyday of that phase of exploration is already over, as people have access to all points of the surface and satellites fly overhead to provide photos and maps at the push of a button. The consequences for society are enormous, of course, as all of us living in the New World can attest.

Curiosity takes us beyond the mere configuration of the surface, however. We want to know what the surface is made of. That's the realm of geological mapping. Although much detailed work remains, in a gross and global sense this task is also complete. We know the kinds and ages of rocks found at the surface almost everywhere. The benefits are profound; this knowledge is basic to modern society, since mineral and energy resources are prerequisites for industry.

But the frontier has not yet run out; beneath the surface the vast interior of the earth remains largely unknown.

". . . we can anticipate a wealth of astonishing new discoveries as buried features of the crust are found, mapped, named, understood, and made familiar. . ."

THE LITTLE-KNOWN REGION OF EARTH'S INTERIOR

A variety of reconnaissance techniques has provided a picture of the gross overall structure of the interior, but only two subdivisions have been explored in detail sufficient to provide a satisfying geological history of those parts of the earth.

One of these structural types, the sedimentary basin, is the habitat of petroleum. For about a century, these basins have been explored with ever-increasing skill and intensity by the petroleum industry. The consequences of this phase of exploration have been astonishing. Our society has been mobilized in great aluminum birds and four-wheeled vehicles and provided at nearly every highway intersection with gasoline at a price less than that of any liquid except water. Who could have imagined these profound consequences a hundred years ago?

After World War II, a second subdivision of the interior, the ocean basins, was explored in detail, and in less than three decades, this activity provided perhaps the greatest advance ever made in understanding the earth: the concept of plate tectonics, which explains how the continents have moved and provides a framework for organizing most of the observations of geology.

SOUNDING AND DRILLING TO STUDY THE DEEP CRUST

This historical perspective is a help in forecasting the future of some branches of geology. It seems reasonably certain that the major frontier of modern earth exploration is the buried continental crust: those rocks, largely hard and crystalline, that stretch from the surface, or the base of the sediments, to the top of the earth's mantle at a depth of about 40 kilometers. At present, the continental crust occupies the role of the ocean basins following World War II; it is explored only spottily and by methods of low resolution, yet there exist techniques used for other purposes that can be adapted to crustal exploration. Seismic reflection profiling and deep drilling, both highly developed by the petroleum industry, are the two principal ones.

Cornell, through its highly successful COCORP project, is a world leader in the application of seismic reflection profiling to study of the continental crust. (See the article by Larry Brown in this issue.) This work is still in an early phase, and one can readily forecast decades of exploration and discovery to come.

Deep drilling for scientific purposes is just getting underway in the United States, but the Soviet Union is currently drilling the deepest hole in the world in old crystalline rocks of the Kola peninsula northeast of Finland. Already over 12 kilometers deep, the hole is targeted for 15 kilometers. The deepest hole in the United States—in sediments of the Anadarko Basin, a petroliferous feature of Oklahoma—is about 9.5 kilometers deep. Preliminary findings are tantalizing. There are reports of open fractures with flowing fluids at all depths, a nonlinear geothermal gradient, and a lack of agreement with structures predicted by geophysical studies.

Left: Cornell is a leader in studying deep crustal structures by seismic reflection profiling, one of the two chief techniques for exploring the earth's basement. The photograph shows researchers in the field, preparing to conduct measurements with the use of truck-mounted vibrators to create signals.

Below: Deep drilling is the other chief research technique for studying the earth's deep basement. Beneath this structure in the Kola Peninsula, Soviet geologists are drilling deep into the earth's crust. The borehole, already more than 12 kilometers down, is the deepest in the world. Drilled as part of a program to investigate crustal structure, this hole is expected to provide continuous information on the long-term thermal regime and physico-chemical processes, as well as a natural laboratory for testing and updating equipment and techniques.

LOOKING AHEAD TO GEOLOGY 2020

More than four billion people now live on Earth, and soon this number will increase to six billion. Since all are dependent on the resources of the planet, it seems certain that societal pressures will mandate the best possible knowledge of those regions that have economic significance. Seismic reflection profiling, deep drilling, and a host of other geological, geochemical, and geophysical techniques will be brought to bear on the continental crust in the near future.

In return, we can anticipate a wealth of astonishing new discoveries as buried features of the crust are found, mapped, named, understood, and made familiar to all earth scientists, just as features of the sea floor have become known in the last few decades. We can expect a new continental tectonics to augment plate tectonics and serve as a framework for organizing the multitude of observations on the continents. We can see the beginnings now. The idea of thin-skinned thrusting as the primary effect of collision is a forerunner of this new era. The related story of terranes that cross the oceanic areas and accrete to form the continents is just beginning to unfold. We shall understand the role of fluids in the deep crust, how they got there, how they transport minerals, how they affect rheology and crustal dynamics, how they may be mined, whether they support life. We can look forward to a near-complete inventory of accessible mineral and energy resources that will outdate the search-for-it-when-needed style of today. The earth mechanisms that cause volcanoes and earthquakes will be better understood and perhaps controlled. At some time, though not by 2020, earth processes will be so well understood and observations so organized and computerized that, sadly, the intellectual challenge of the science will be reduced. But in the decades ahead, the continental basement will be an important and exciting frontier.

Other branches of geology also seem ready for major advance. For example, the field of evolution, which lay somewhat fallow after the impact of the powerful ideas of Darwin, seems fertile again; the current debates over punctuated equilibrium and the effects of impacts of extraterrestrial bodies serve as forewarning.

Computers are sure to impact geology heavily, both in research, where the effects are already felt, and also in earth-science instruction, where so far little progress has been made in using the unique capability of this powerful tool. One can imagine the development of a computer model that would accommodate in an optimal way the huge quantity of observational data on the earth, and anticipate the construction of forward models of the planet as it evolves through geologic time.

And, of course, there is fascinating opportunity in study of the planets, sun, moons, and other bodies of the solar system whose stories must be pieced together in a history common with that of Earth. Thirty-six years ago none of us dared hope that we would hold in our hands a piece of the moon, as many geologists now have. Perhaps by 2020 geologists will find samples of other planets, moons, asteroids, and even the deepest, most inaccessible

parts of the continental crust, commonplace. The era begun by Columbus, Magellan, Cook, and others who sought observation and comprehension of the earth in a global sense is not yet over, nor will it be by 2020.

An earlier version of this paper was presented as the 1984 commencement address at the Virginia Polytechnic Institute Department of Geological Sciences.

Jack Oliver, the Irving Porter Church Professor of Engineering, came to Cornell in 1971 as chairman of the Department of Geological Sciences and supervised its reorganization and development as an intercollege unit. Currently he is a leader of the Consortium for Continental Reflection Profiling (COCORP), which is centered at Cornell, and director of the Institute for the Study of the Continents (INSTOC).

Oliver was educated at Columbia University, earning the doctorate in 1953, and remained to work at the Lamont-Doherty Geological Observatory there. He was a member of the Columbia faculty for sixteen years and served as chairman of the geology department from 1969 to 1971.

He has served as a consultant to government agencies and on many panels of the National Academy of Sciences and of various international scientific organizations. He is currently chairman of the United States Committee on Geodynamics. He is a former president of the Seismological Society of America and a member of many other professional societies.

Among the honors he has received are the Walter Bucher Medal from the American Geophysical Union (1981), the Virgil Kauffman Gold Medal from the Society of Exploration Geophysics (1983), and the Medal of the Seismological Society of America (1983). He is a fellow of the American Geophysical Union and of the Geological Society of America, and earlier this year he was elected to the National Academy of Sciences.

EXPLORING THE EARTH BENEATH THE CONTINENTS

by Larry Brown

How the Appalachian Mountains were thrust up when Africa collided with North America some 30 million years ago; how the western United States is now being pulled apart; active magma chambers lurking beneath New Mexico and Death Valley; and "plumbing" that may have formed the Mother Lode gold deposits of California.

These are a few of the major geological discoveries that have been made by the Cornell-based Consortium for Continental Reflection Profiling (COCORP). The COCORP project has turned technology developed by the oil-exploration industry toward the solving of fundamental questions about the composition, structure, and evolution of the continents.

THE SEISMIC REFLECTION PROFILING TECHNIQUE

Beginning with its first field experiment in the spring of 1975, COCORP has used seismic reflection profiling to map structures deep within the continental crust. This technique, similar to radar and sonar, uses acoustic (sound) waves to probe variations in rock composition at depth. Developed primarily to look for oil and gas deposits in sedimentary basins, this geophysical method has been used effectively by COCORP to map rock structures at much greater depth and in areas that have more scientific than economic interest.

The research program is conducted under the direction of faculty, staff, and students in Cornell's Department of Geological Sciences. Principal investigators at the present time are Jack Oliver, Sidney Kaufman, and myself. The consortium also includes scientists from Rice, Dartmouth, Wisconsin, and Princeton.

The field measurements are carried out by a professional seismic surveying company (Geosource, Inc.). Large truck-mounted vibrators are used to generate elastic waves in the ground. These waves travel downward and are partially reflected from discontinuities in subsurface rock units, creating reflected signals that are recorded by a 10-kilometer array of detectors, or geophones, deployed along the surface. Over 2,300 geophones in ninety-six independently recorded groups register more than 700 million bits of information each day on magnetic tape.

These tapes are sent to Cornell to be processed by COCORP students and research staff on a computer system, the *Megaseis* (a trademark name belonging to Seiscom Delta), which is specifically designed for processing seismic data. After considerable signal enhancement and analysis on the computer, there emerges an image of the earth's deep crust that is suitable for geological interpretation.

Since the COCORP field crew operates year-round, COCORP researchers stay very busy, not only processing and interpreting the tremendous volume of new data as they roll in—a time-consuming procedure in itself—but planning and preparing for future field work. Locating roads suitable for a seismic survey, obtaining permission from appropriate agencies and individuals, or arranging for alternate locations if weather should prove uncooperative (it too often does) may require as much attention as analyzing

COCORP uses vibrator trucks to obtain seismic reflection data. These trucks were in operation in the Basin and Range of Utah.

the seismic data. Fortran computer codes and county land-use permits sometimes seem equally inscrutable!

Although the logistics of maintaining a continuous program of field surveying while at the same time scientifically evaluating the results are demanding, COCORP's efforts have been more than justified. COCORP surveys in areas such as the southern Appalachians and the Basin and Range of the western United States have helped revolutionize geologic thinking about the origin and evolution of mountain belts, rift valleys, and the continents they form.

NEW DISCOVERIES ABOUT APPALACHIAN HISTORY

Some of COCORP's most important findings to date are from its surveys in the Appalachian Mountain belt. This ancient system, formed between 200 and 500 million years ago, represents the breakup and subsequent reassembly of a large continental mass that included parts of what is now North America, Europe, and Africa. Initial breakup of the megacontinent formed an ocean, Iapetus, similar to the present Atlantic. Within this ocean formed island arc systems like those that now ring the Pacific. Beginning some 450 million years ago, this ocean began to close; the island arcs and other crustal fragments were swept onto the edge of what was to become North America. Ultimately, North American and African continental fragments collided, forming a new supercontinent, Pangea. Pangea later split again to form the modern Atlantic Ocean.

While this history of the Appalachians was being worked out by geologists studying rocks at the earth's surface, COCORP began to survey the roots of the mountain belt. Those surveys soon overturned conventional notions about how the Appalachians were put together. It was found that the surface rocks are a poor guide to the geology at depth: in fact, they are part of a relatively thin sheet that had been thrust 300 kilometers or more northwestward from a source region far to the southeast. Pushed underneath the deformed and metamorphosed rocks in this thrust sheet was a dramatically different sequence of rocks—relatively underformed sedimentary strata that had been deposited near the surface while the rocks now above them were being heated and deformed at great depth elsewhere.

By tracing out the subhorizontal geometry of the fault which juxtaposed these very different rock types, COCORP demonstrated that the Appalachians formed not by lateral accretion of new continental material along steeply dipping "sutures," but by overthrusting of major rock units for long distances. This overthrusting created a rock "sandwich" in which wet, sedimentary rocks were trapped between older, metamorphic rocks. One exciting implication of this process is that water squeezed out of the trapped sediments may have fluxed through the overlying crystalline rocks to deposit ore bodies. Another is that the buried strata may still contain economic reserves of hydrocarbons.

COCORP has now surveyed additional lines in the Appalachians to look at variations in this basic model of

Figure 1

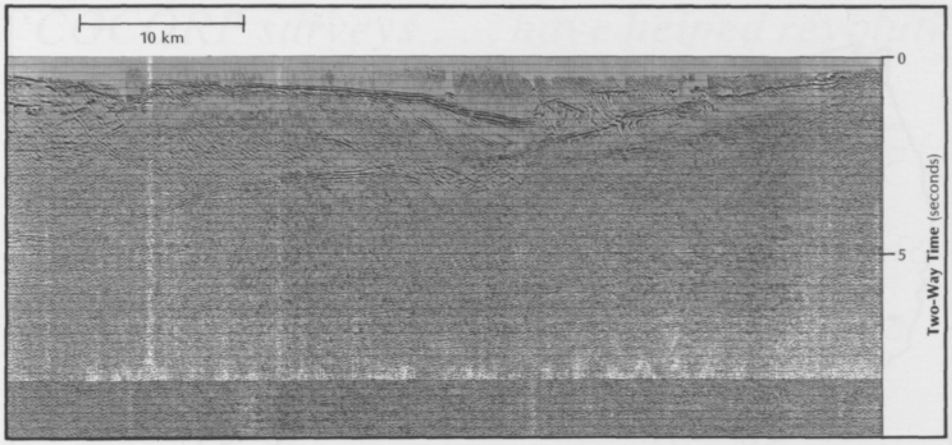


Figure 1. A portion of COCORP's seismic section from the Sevier Desert in west-central Utah. The strong reflection dipping westward is a major extensional fault controlling the breakup of the continent in this area. Seismic signals were initiated and recorded after reflection at sites spaced 100 meters apart along the surface. The vertical axis represents two-way travel time in seconds; one second corresponds to about 3 kilometers of depth.

mountain-building. The latest work, in southern Georgia and northern Florida, appears to have found the specific fault—previously unknown—across which North America and Africa were once joined.

THE PULLING APART OF NORTH AMERICA

Whereas the Appalachians represent an area in which ancient continents once collided, the Basin and Range province of western Utah and Nevada is where the present North American continent seems to be in the process of pulling apart. The characteristic series of mountain ranges and intervening valleys that give this province its name result from the breaking up of the surface under lateral extension. The faults along which this breakup is occurring are usually steeply dipping at the surface. It has long been speculated that these faults extend completely through the crust into the underlying mantle; however, a recent COCORP survey has found a radically different arrangement.

COCORP's survey in west-central Utah traced a key fault of the Basin and Range deep into the crust (Figure 1). Instead of dipping at a high angle, this fault—termed the Sevier Desert detachment—was found to dip very gently to the west, splaying out in the lower crust into a complex zone of faults. Significantly, the steep normal faults evident at the surface do not extend through the underlying low-angle fault; therefore, the Sevier Desert detachment must be the key structure in the process of crustal extension in this area. Its geometry may be an important clue for inferring the rheology of the deep crust. An exciting possibility suggested in part by COCORP's Appalachian and Basin and Range results is that low-angle compressional faults, such as those formed during continental collision, may be reactivated to accommodate later continental breakup.

The remarkable success of COCORP's Utah survey spurred a major effort over the past year to complete a survey across the entire Basin and Range province. This survey, stretching from central California to central Utah, is the longest deep seismic reflection traverse yet completed on land (Figure 2). Results from that traverse, which are still being analyzed, have already greatly modified our ideas about how continents pull apart.

CONDUITS FOR MAGMA AND ORE-BEARING FLUIDS

Tracing the geometry of important faults is not the only way COCORP has thrown new light on continental geology. Unusually strong reflections detected in one of the earliest surveys in New Mexico were interpreted to be from a mid-crustal magma chamber. Now, a new survey in Death Valley, southern California, appears to have found another one (Figure 3). An especially interesting aspect of these new results is a dipping reflection that can be traced from the inferred magma chamber up to the surface. At the surface is a young volcanic cinder cone. The conclusion that COCORP is seeing, for the first time, a conduit that magma travels from depth to the surface is hard to escape.

Figure 2

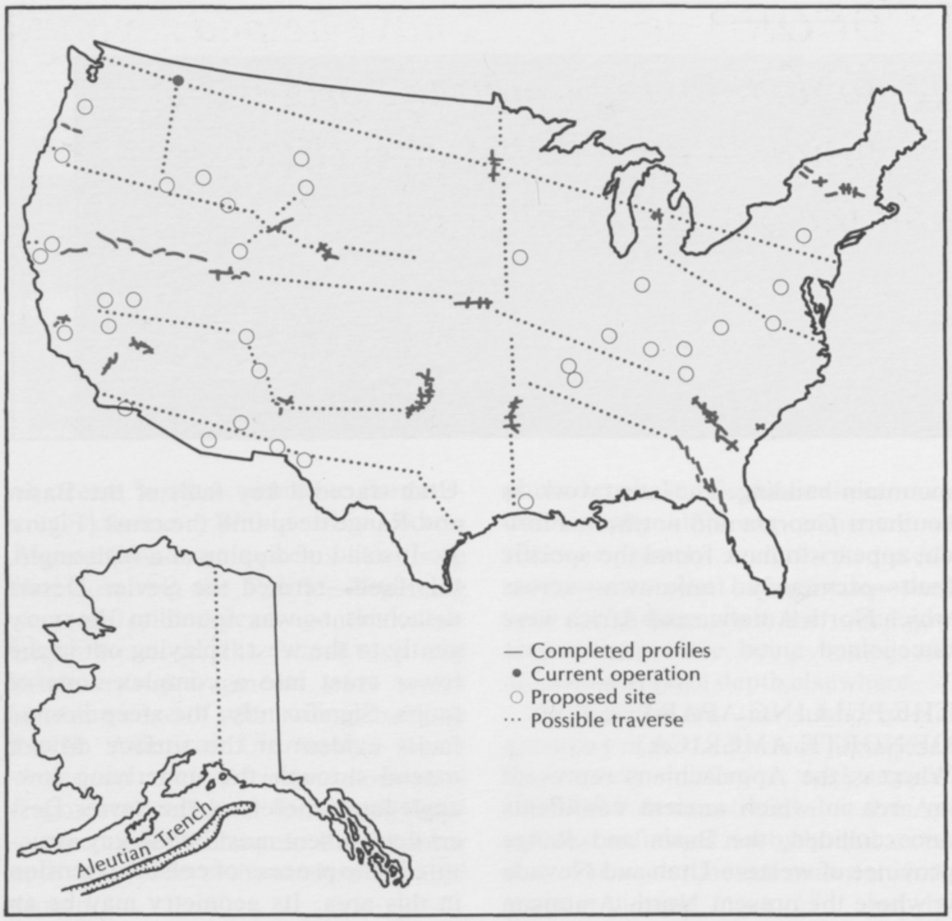


Figure 3

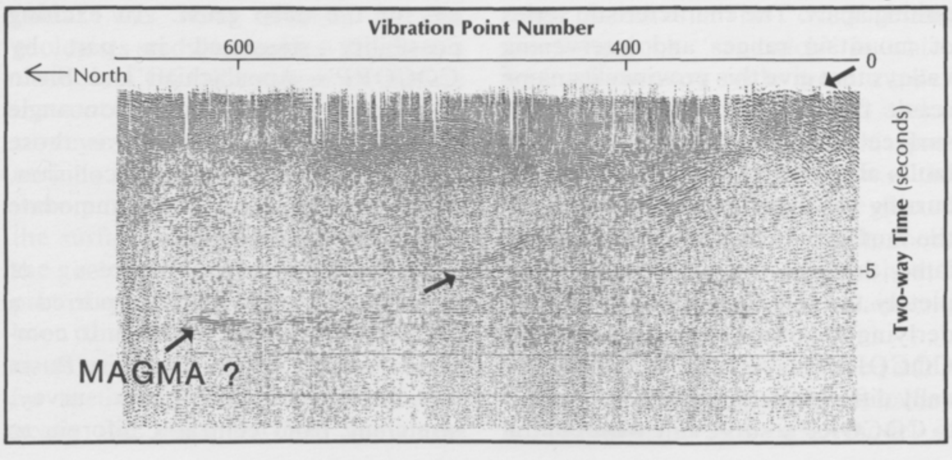


Figure 2. Location of COCORP surveys completed to date (solid lines in color), along with possible sites of future work (open circles) and a grid of transcontinental transects (dotted) that serve as a basis for long-term planning. Now under development are specific plans for work on the transect across Alaska, which will use roads along the trans-Alaska pipeline.

Figure 3. A COCORP seismic section from Death Valley, showing a strong reflection that may be a magma chamber. An arrow points to this reflection, or "bright spot," at about 6.5 seconds, which corresponds to a depth of about 18 kilometers. The dipping reflection between the other two arrows appears to be due to a fault that may have conducted magma to the surface: a geologically recent volcanic cinder cone lies at the surface position of this fault.

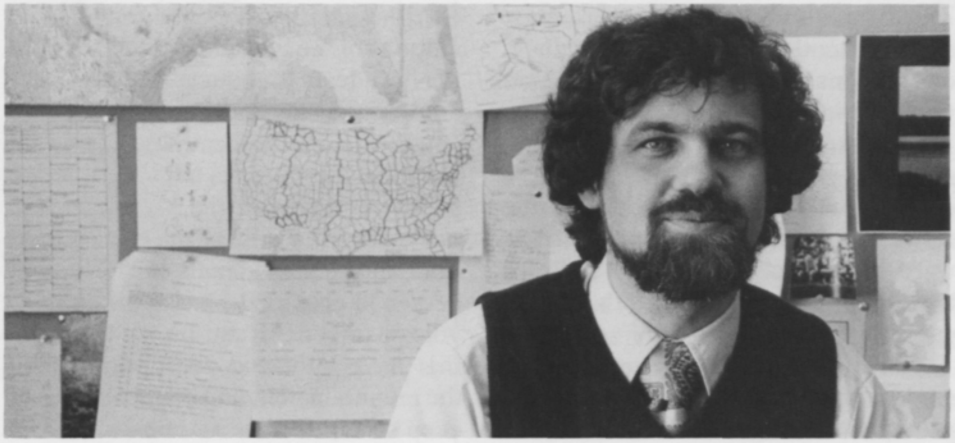
"COCORP surveys . . . have helped revolutionize geologic thinking about the origin and evolution of mountain belts, rift valleys, and the continents they form."

Crustal plumbing of another kind may be revealed by COCORP surveys in northern California, where a survey across the Sierra Nevada maps a series of moderately dipping fault zones from the surface to middle and lower crustal depths. Some of these faults may have served as conduits for the circulating fluids that deposited the lodes of "Gold Rush" fame.

COCORP'S LEAD IN STUDIES OF CONTINENTS

From these few examples, it is clear that COCORP research is having a major impact on our evolving understanding of the continents. As COCORP enters its second decade of operation, it continues to push into new frontiers of exploration. New technology, new processing, and new surveys in areas such as Alaska and on other continents are being considered. Expansion of COCORP's field effort with a second full-time field crew may soon be possible.

COCORP's success has spawned similar programs in continental reflection profiling in at least a dozen other countries. COCORP must, and will, work hard to maintain its leadership position in the exciting new era of continental exploration now opening up.



Larry Brown, associate professor of geological sciences, earned his doctorate at Cornell in 1976 and remained in the department as a postdoctoral associate and then as a member of the faculty. His thesis research was on recent crustal movements, and his current work centers on deep seismic reflection studies.

Brown received his undergraduate degree in physics (with highest honors) from the Georgia Institute of Technology in 1973. Soon after completing his graduate studies and joining the Cornell faculty, he received the ARCO Outstanding Junior Faculty Award. During the summer of 1983 he was a guest professor in the Institut für Geophysik at Christian Albrecht Universitat in Kiel, West Germany.

He is a member of several honorary societies and of the American Geophysical Union, the Society of Exploration Geophysicists, and the European Union of Geosciences.

THE CORNELL ANDES PROJECT

Studies of Mountain-Building Processes in Action

by Bryan L. Isacks

The Andes and Himalayan mountain systems are the world's most dramatic expressions of the effects of the convergence of two lithospheric plates. Yet they are quite different. In the case of the Himalayas, two continents have collided, while beneath the Andes, the suboceanic Nazca plate bends downward and descends into the interior beneath the overriding South American continental plate.

The Andean *subduction zone* is of great interest because it is the simplest example of the formation of mountains where continental and suboceanic plates converge. In other more complex mountain belts, an Andean-type convergence is thought to be an important early phase whose effects are very difficult to disentangle from those of later processes such as continental collision. In the Rocky Mountains, for example, an Andean-type phase was associated with the formation of major oil-bearing structures, including the well-known "Overthrust Belt," but their present relief is the result of events that occurred in a quite different plate-tectonic framework.

Although the gross geometry and motions of the two converging plates in the Andean subduction zone are known, we still understand very little about the mechanical, thermal, and chemical interactions between the two plates, or between the plates and the convecting material of the earth's interior. Indirect evidence of these processes is provided by the patterns of volcanism, deformation, and uplift that have built and continue to build the mountain belt, and by the images of deep structure that we construct from analyses of earthquake locations, seismic waves, and other geophysical data.

The Cornell Andes Project tries to integrate these strands of evidence, developed by quite a diversity of disciplines, in order to elucidate the fundamental processes that are at work. This is necessarily a multidisciplinary effort utilizing a broad range of data from traditional field studies, satellite images, and remotely monitored geophysical sensors. Cornell researchers involved in the Andes Project include Muawia Barazangi and me, who study earthquakes, topography, and gravity; Richard W. Allmendinger, who studies seismic reflection profiles and young faults; Teresa E. Jordan, who studies basin formation and the timing of deformation and magmatism; Arthur L. Bloom, who studies landform evolution; and Suzanne Mahlburg Kay, who studies the chemistry and timing of the volcanism. Eight graduate students are currently doing thesis research on the Andes Project.

RELATING SURFACE AND DEEP STRUCTURAL FEATURES

An important characteristic of the Andes that closely ties observable surface features to deep structures gives us a very useful handle on the problem. Along the main latitudinal trend of the Andes, major variations in the characteristics of the mountain belt can be closely correlated with the shape of the overridden Nazca plate. The major segments of the mountain belt correspond to plate segments with angles of inclination that alternate between 30 degrees and nearly horizontal. The

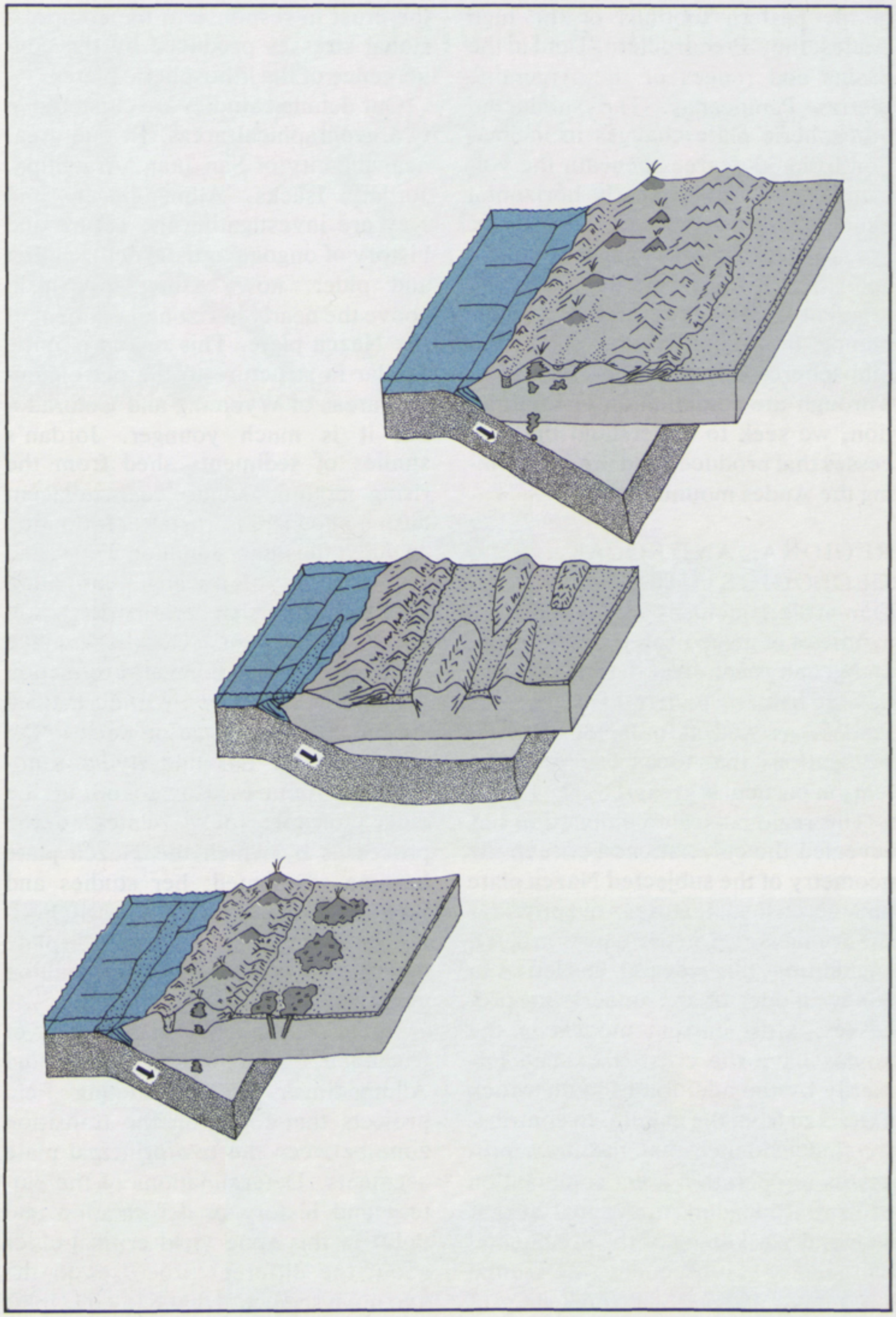


Figure 1. Regions of the Andes under study in the Cornell project. The mountain building is the result of subduction of the Pacific plate under the North American plate. Data acquired in the project have shown that surface features are correlated with characteristics of the underlying lithospheric plate: In the northern segment, the 30° inclination of the underlying plate is associated with active volcanism. Farther to the south, where the underlying plate is nearly horizontal, there is little or no volcanism, but the basin-and-range formations of the Sierras Pampeanas show that there has been crustal deformation.

most striking correlation is between the nearly horizontal segments of the Nazca plate, and a complete absence of the active or geologically young volcanoes that are so prominent a feature of other parts of the Andes. This correlation suggests that the existence and shape of the wedge of subcrustal material located between the converging plates is critical to the generation of volcanoes and to other processes going on in the overriding plate.

In the Cornell Andes Project we focus on two of the segments located in the central Andes (see Figure 1). The northern segment has hundreds of volcanoes, including many of the world's highest, whose edifices sit atop a broad uplifted area nearly four kilometers in average elevation, fifteen hundred kilometers in length, and three hundred kilometers wide. In the other segment, to the south, the area of very high elevation becomes significantly narrower, and for a distance of nearly seven hundred kilometers along the main mountain chain, there are no volcanoes. There is, however, evidence of youthful crustal deformation

". . . we seek to understand the processes that produced and are still forming the Andes mountains."

in the eastern foothills of the high Andes, the "Precordillera," and in the basins and ranges of the Argentine Sierras Pampeanas. The subducted lithospheric plate changes in inclination from 30 degrees beneath the volcanic cordilleras to nearly horizontal beneath the nonvolcanic cordilleras. We are investigating changes in crustal and lithospheric properties from one segment to the other, and also determining the shape of the subducted lithosphere beneath the segments. Through the combination of information, we seek to understand the processes that produced and are still forming the Andes mountains.

REGIONAL AND LOCAL GEOLOGIC STUDIES

Our project includes a regional-scale synthesis of geological, topographical, and geophysical data—a kind of study never before undertaken for the Andes—as well as more detailed investigations that focus on key problems in particular areas.

The regional-scale compilation has revealed the correlations between the geometry of the subjected Nazca plate and the surficial features, and provides the framework for the entire project. In addition, this research has led us to a new model of the underlying processes. Most current models of the Andes have the crust thickened primarily by the addition of molten rock extracted from the mantle. In contrast, we find evidence that the main processes in operation are a combination of heating, leading to thermal expansion and weakening of the continental plate, and subsequent horizontal shortening and vertical thickening of the crust in response to the compressional stresses produced by the convergence of the lithospheric plates.

Our detailed studies are clustered in two geographical areas. In one area, near the city of San Juan, Argentina, Jordan, Isacks, Allmendinger, and Kay are investigating the nature and history of ongoing crustal deformation and older, now extinct volcanism above the nearly horizontal segment of the Nazca plate. This region is quite similar in structure to the petroleum-rich areas of Wyoming and Colorado, but it is much younger. Jordan's studies of sediments shed from the rising mountains into deep adjacent basins show that crustal deformation spanned the last ten million years, and the seismicity Barazangi and I are studying shows that deformation is still an active process. Our earthquake studies and Allmendinger's reflection seismology help us tie the surficial structures to deformation deep in the crust and to the underlying lithospheric structures. Kay's work on the older volcanic rocks relates to the processes by which the Nazca plate became segmented; her studies and Jordan's indicate that the nearly horizontal inclination of the Nazca plate may have developed only ten million years ago.

In the second area, near the city of Tucuman, Argentina, Bloom and Allmendinger are conducting field projects that focus on the transition zone between the two principal plate segments. Determinations of the pattern and history of deformation and uplift in this zone yield critical clues about the different processes in the two main segments that flank it. Uplift

1

2

Photographs from the Cornell Andes Project show some of the features under study. 1. Researchers from Cornell and the Argentine Geological Service collect volcanic ash samples from a sedimentary rock formation. A fission-track technique is used to establish the absolute ages of the specimens. 2. These young deformed sedimentary rocks in the Santa Maria valley are from the transition zone between the northern volcanic and the nonvolcanic segments of the Andes (see Figure 1). These rocks are less than 10 million years old. 3. Thrust faults (traced by the barbed lines) are an indication of deformation of the Andes. 4. This cinder cone and flows in the northern segment are an indication of recent volcanic activity.

3

4

and faulting are indicated by Bloom's analysis of landforms, especially the terraces and gravel slopes mantling the intermontane valleys. Allmendinger's examination of successive senses of displacement across faults reveals the pattern of deformation in space and time. Newly acquired imagery from the Space Shuttle and satellites complements the field data.

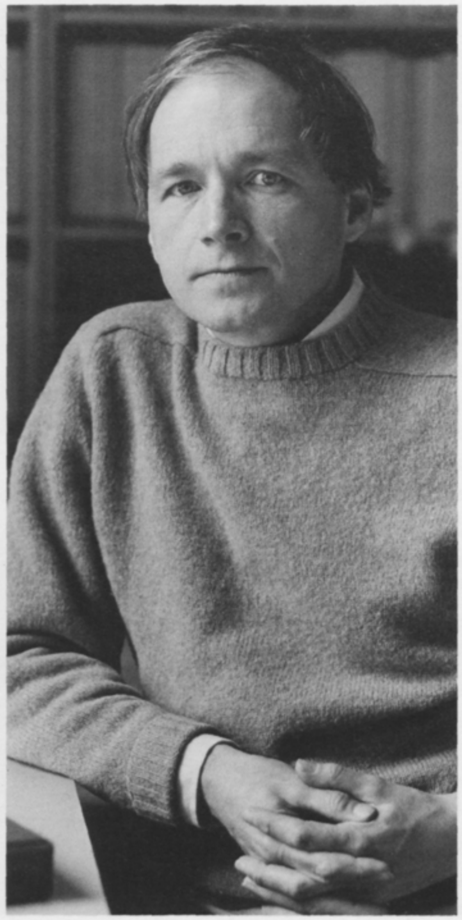
COORDINATED WORK ON A LARGE-SCALE STUDY

The Andes Project is an ambitious undertaking, for it is concerned with a large, relatively poorly mapped region extending into three countries—Argentina, Chile, and Bolivia. Although we have extracted much useful information from very extensive searches of the literature, much of it available only in South America, and from syntheses of these data across national boundaries, the most critical sources of new data are produced by satellite sensors and by other forms of remote sensing, such as detection of earthquakes by the international global seismograph network.

Remote-sensing techniques have an enormous impact on the strategy for studying regions such as the Andes that are too large and inaccessible to be effectively covered by the traditional methods of field geology. Instead, field work can now be much more sharply focused on specific localities and problems critical to our understanding of the fundamental regional-scale processes. The Andes Project, as well as other, similar work in the Department of Geological Sciences, will benefit greatly from the recent acquisition of a powerful computerized system for processing images, a facility that is necessary to exploit the large and rapidly increasing satellite and geophysical data banks. (See John M. Bird's article in this issue for a discussion of the system.)

The Andes Project demonstrates the effectiveness of combining many approaches and techniques in an integrated study of a geologically significant region. The project calls on the expertise of specialists in various fields of geological science, and utilizes methods ranging from the detailed examination of sediments to satellite imagery. It encompasses both the geologic history of a region and the present conditions, integrating them into a description that extends through time and space. It explores at depth as well as on the surface, correlating the crustal structures and processes with those of the underlying lithospheric plates.

What is emerging is not only a large amount of information, but a better understanding of fundamental geologic processes. Through learning about the Andes, we learn about Earth.



Bryan L. Isacks, professor of geological sciences at Cornell since 1971, is a specialist in seismology and tectonics. He was educated at Columbia University, earning the A.B. degree in 1958 and the Ph.D. in 1965. Before coming to Cornell, he conducted research at the Lamont-Doherty Geological Observatory at Columbia and served as an adjunct associate professor.

Isacks has studied the seismology of the various parts of the world, including the Tonga, Fiji, and New Hebrides island arcs. He has also participated in geophysics research in the Arctic region and in petroleum exploration using seismic reflection profiling. In addition to participating in the Andes Project, he is currently cooperating with French seismologists in the study of earthquakes in the New Hebrides island arc and is developing the computerized image-processing system mentioned in this article.

He is a fellow of the American Geophysical Union and the Geological Society of America, and was elected to the board of directors of the Seismological Society of America for two terms.

THE DEFORMATION OF SEDIMENTS IN MOUNTAIN BELTS

by Daniel E. Karig

Highly lithified, strong, and dense sedimentary rocks, such as those used in many of Cornell's buildings, evolved from a very soft and highly porous state at the sediment-water interface. Such evolution may occur without much deformation, under the load of subsequently deposited sediment, but in mountain belts and other zones of major earth movement, sedimentary rocks are often deformed, sometimes extremely so.

In the past, it was tacitly assumed that most of this deformation occurred after the sediments were lithified, but it has become increasingly obvious that this is not generally true. Much of the deformation now observed in mountain belts occurred near the deep-sea trenches that mark converging plate boundaries. In that setting, soft sediments are scraped off the descending oceanic plate and accreted to the inner trench slope, which later is uplifted and incorporated into a mountain belt. During this process, deformation and lithification progress simultaneously.

The deformation that develops under these conditions is not so much large-scale folding and faulting as a pervasive distortion on a small scale. One intriguing form is *melange*, an incredibly sheared and disrupted mass consisting of many different rock types and found as sheets or bands in almost all mountain belts. The origin of melange has been the cause of sometimes heated argument for almost a century and still defies adequate explanation. It is quite clear that melange and a host of other highly deformed rocks develop somewhere near trenches, but where, in what mechanical state, and by what process? Various possibilities have been suggested. Perhaps shearing in deep, diffuse fault zones is the cause; perhaps the deformation occurs as a result of mixing in immense submarine landslides.

Advances in the understanding of sediment deformation are coming from such approaches as geologic study of marine trenches, detailed structural analysis of lithified sediments in mountain belts, and laboratory simulation of natural sediment deformation. A difficulty is that these approaches involve quite widely separated geoscientific disciplines and have seldom been integrated in a way that provides reinforcing evidence. Now, however, these different approaches are being combined in a study of the Southwest Japan Arc that involves several of us at Cornell.

MARINE STUDIES OF AN ISLAND ARC SYSTEM

In the offshore trench of the Southwest Japan Arc, seismic profiling and deep-sea drilling show that sediments from the ocean floor are being accreted to the Japanese margin in thrust sheets (see Figure 1). These thrusts, it is now recognized, play a major role in shaping the inner trench slope, and account for much of the deformational fabric; however, almost half the convergence is absorbed by structures, too small to resolve seismically, that are diffused within the thrust sheets. The massive slides once proposed have not been observed—not in the Japan Arc, not in any arc. What does occur is a concentration of smaller slumps at the toe of the frontal thrust, and since the material there is subsequently carried be-

Figure 1a

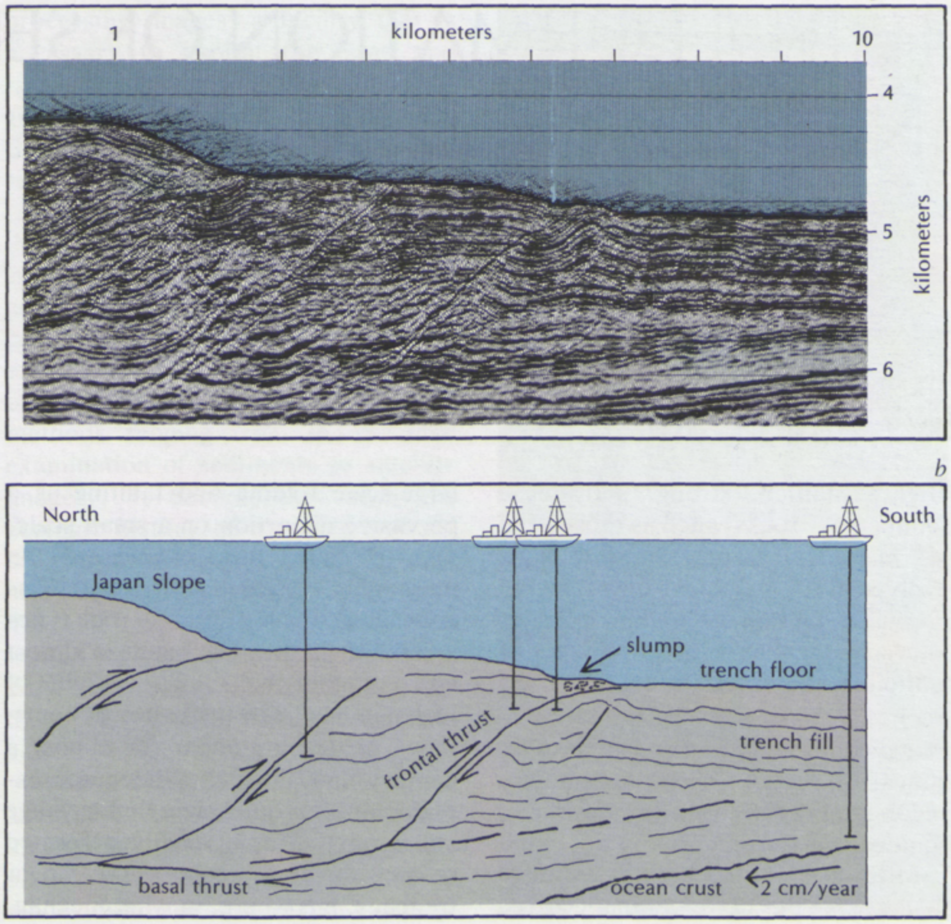


Figure 1. A seismic reflection profile (a) *and interpretive section* (b) *across the Southwest Japan Trench of Shikoku. This profile shows the beginning of deformation at the foot of the inner trench slope, and the approximate location of deep-sea drill holes.*

"...we believe we will provide an important part of the solution to a long-standing problem in geology."

neath the thrust mass, some shearing is superimposed on the slump fabric. This may produce some melanges, though certainly not all.

Deep-sea drilling in the trench and lower slope has provided a wealth of detailed information about the physical properties and structural fabric of the accreted sediments, and these data permit us to estimate the mechanical state of the material. The diffuse deformation is probably partly ductile, but it has also produced shear fractures that become more prevalent with increasing depth. The orientation of these fractures, together with the geometry of the major thrust faults, indicates not only the orientation of the stress tensor, but also the magnitude of some stress components. These struc-

Figure 2

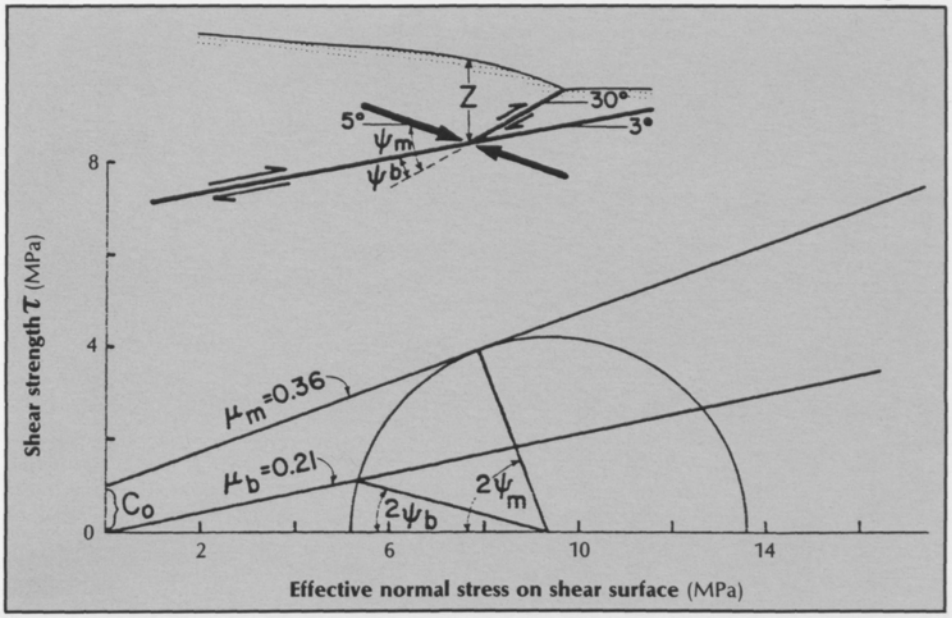


Figure 2. A Mohr diagram and mechanical model for the deformation at the foot of the trench slope shown in Figure 1. In the diagram, the shear strength (τ) is determined from the relation $\tau = C_0 + U_m\sigma_n'$, where cohesion ($C_0$) is measured in drill cores, the "internal friction" (U_m) is calculated from observed shear fractures, and the effective normal stress on the shear surface (σ_n') is deduced from the large-scale structural pattern.

tures can also be used to determine such mechanical parameters as the coefficients of internal and sliding friction (see Figure 2). In addition, the drilling data, together with geophysical data and measurements of the shape of the deformation zone, have allowed us to determine the distribution of deformation across the slope, as well as the rates at which Japan and the Philippine Sea plate are converging.

COMBINING LAND-BASED WITH MARINE STUDIES

As important as it is, deep-sea drilling has not provided enough data to solve most of our problems. In part, this is a result of the very difficult technical problems encountered in attempting to penetrate the unstable sediments of the deforming zone. We have come to realize that the incomplete recovery of small cores of sediment that have been disturbed by the drilling operation leaves too much of the structural fabric to the imagination. An additional important limitation is that even with the most advanced drilling techniques, the deeper and presumably more highly deformed sediments cannot be reached.

These deeper levels of the accreted sediments can be studied, however, in mountain belts that have been exposed by uplift—a process caused by continued convergence and erosion or by the collision of continents. On the island of Shikoku, directly north of the drill sites, sediments accreted at the trench 20 to 100 million years ago are widely exposed and reveal many of the structural features formed at greater depth. In cooperation with Japanese geologists from Kochi University, we have begun detailed structural studies of the youngest of these rocks, which display a range of deformation from melange to highly coherent, but tightly folded, bedding.

In these sediments we see a progression of structural styles that can be attributed to progressive lithification, as well as to a changing strain field. The interaction of structural geometries reveals the sequence of deformational events, and to some extent implies the physical and mechanical state of the material when each structure was formed. Of course, we now see only the cumulative result of the deformational spectrum and the final mechanical and physical state; all the earlier states must be inferred, and most of the earlier structures have been badly degraded by younger deformation. For these reasons, we have very little information about the path those rocks followed in time and space from the ocean floor to their present outcrops.

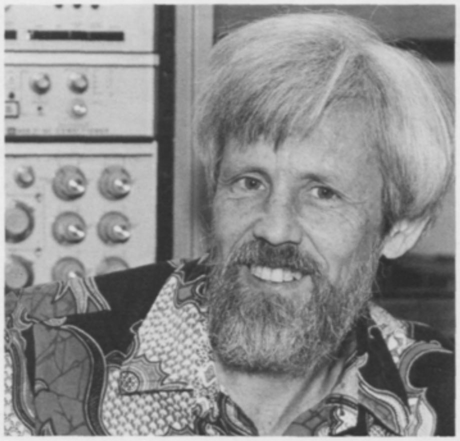
Figure 3

Figure 3. Very ductile folds in highly deformed sediment accreted from the trench and exposed in Shikoku. This sediment was probably deformed in a slump similar to that shown in Figure 1.

We can restrict the possible paths by using what we do know about the nature and distribution of deformation and of mechanical properties in the more active region near the trench. For example, we know that early, extremely ductile, and discontinuous folds (Figure 3) probably developed in the slumps at the toe of the frontal thrust (Figure 1). We can also obtain some idea of the mechanical state that existed during development of a phase of deformation by observing the style of structures that resulted. Thus, early ductile folds reflect very high porosity, whereas the later brittle structures indicate deformation at lower porosities and higher effective stresses.

THE CONTRIBUTION OF LABORATORY STUDIES

This approach is limited, however, by the very rudimentary correlation that exists between physical and mechanical properties and the resultant structural style. One might think that these relationships would have been developed long ago through experimental research, but for several reasons the behavior of moderately porous sediments has been largely ignored. One reason, which I have already mentioned, is that until recently, geologists did not attach much importance to deformation in "soft sediments." Also, these sediments have properties that are intermediate between those of soils and rocks, and therefore are difficult to work with using existing equipment. The sediments are less porous and stronger than the soils investigated by geotechnical engineers,



whose test apparatus is seldom capable of handling the high stresses needed; on the other hand, geophysical rock mechanics is concerned with the behavior of very low-porosity rocks, generally at much higher stresses.

We are attempting to develop correlations between mechanical properties and structural states of soft sediment through a research program of experimental deformation. In the new Snee Hall is a large laboratory for experiments on sediment deformation that will use equipment we have been developing for several years. The centerpiece of the laboratory is the computer-controlled, servo-hydraulic load frame for applying loads to a test cell in which we can measure axial and radial stresses, as well as changes in pore-water volume and pressure. Some of the test samples will be cores collected from deep-sea drilling sites, but since there are not enough of these cores to show an adequate range of properties, we will supplement them with prepared samples of predetermined composition and porosity. These samples will be created under natural loading conditions in a second load frame and consolidation cell.

Because deformation in sediment is not homogeneous, we plan to examine the results of our experiments in the microdomain, using optical and electron microscopic techniques. Those techniques have had very little application to rock mechanics, but the various elements are well established in related disciplines. In this we are extremely fortunate to have the help of other Cornell researchers in relevant areas of structural geology and geomechanics; they include Andy Ruina of the Department of Theoretical and Applied Mechanics, Dave Kohlstedt of Materials Science and Engineering, Tom O'Rourke of Structural Engineering, and Maura Weathers and Rick Allmendinger of Geological Sciences.

With the help of all these Cornell specialists, and the physical rseources afforded by the new building, we believe we will provide an important part of the solution to a long-standing problem in geology.

While he has been at Cornell, Daniel E. Karig, professor of geological sciences, has participated in numerous oceanographic expeditions, including two cruises of the Deep-Sea Drilling Project, and has undertaken field research in Indonesia, the Philippines, Iran, and—as indicated in this article—the Southwest Japan island arc system.

Karig studied geological engineering as an undergraduate at the Colorado School of Mines, and took his graduate education at the Scripps Institute of Oceanography of the University of California at San Diego. After receiving his doctorate in 1970, he spent a year as a marine geologist at the Scripps Institute and two years on the faculty of the University of California at Santa Barbara before joining the Cornell faculty in 1973.

In 1979 he was awarded the Edmond C. van Diest Medal by the Colorado School of Mines, and in 1982 he was elected an honorary foreign member of the Geological Society, London. He is a fellow of the Geological Society of America and a member of the American Geophysical Union, the Geological Society of Malaysia, and Sigma Xi.

THE EARTH'S INTERIOR

by William A. Bassett, John M. Bird, and Maura S. Weathers

Because there is no direct access to the interior of the earth, exploration of that region must be carried out indirectly. Petrologists study rocks such as kimberlites (a source of diamonds) that come from depths of several hundred kilometers. Seismologists deduce structural features by analyzing seismic waves that travel through the earth. Mineralogists subject minerals to high pressures and temperatures to determine the properties of these substances at conditions that exist within the earth.

The integration of results from these sources is providing a better understanding of the nature of Earth's interior. Because of these techniques, and new ones that are being developed, the next decade or so can be expected to be a time of significant advance in the study of the interior of the planet.

Geologists at Cornell are contributing to this exploration in several programs of research. In this article we describe three investigations we are conducting. One is an experimental study in which we are determining the conditions under which diamond melts, and the implications for earth processes. Another is a project in which very intense x-rays from the University's synchrotron are used to study phase transitions in certain significant minerals. The third is a study of rocks and minerals that we believe actually originated in the earth's deep interior.

THE MAJOR REGIONS: LITHOSPHERE, MANTLE, CORE

These specific and finely detailed studies are directed to a very large-scale subject: the whole earth, extending from the crust on which we live to the unreachable center. The principal regions of the interior, as diagrammed in the illustration on the inside front cover, are the lithosphere, the mantle, and the core.

The lithosphere is composed of oceanic and continental crust and some mantle rock. It is segmented into a number of relatively rigid plates that are continuously generated and consumed into the mantle in response to underlying processes. The recent advances in understanding the motions of the lithosphere have established that during intervals of about 400 million years, approximately 70 percent—the sea floors—of the earth's lithosphere is exchanged by plate evolution. Continents "drift" because of plate evolution, and plate evolution is the principal mechanism by which the planet's internal heat is dissipated.

The bulk of the mantle, more than 60 percent of the mass of Earth, extends downward from beneath the lithosphere to the core, at a depth of approximately 2,900 kilometers. Seismic studies show that the mantle is stiffer than steel. However, because the silicates and oxides that constitute the mantle are almost at their melting temperatures, viscosity is low enough so that convective flow could occur. Because the magnitude of heat flowing from the earth is greater than would be expected by simple conduction, it is believed that the mantle is convecting and that this convection drives the lithosphere plates.

The region just below the lithosphere, the asthenosphere, is the source of much of Earth's volcanism.

"...the next decade or so can be expected to be a time of significant advance in the study of the interior of the planet."

The asthenosphere has relatively very low viscosity because the pressure-temperature conditions of that part of the mantle are very close to the conditions that result in melting. The asthenosphere is the region of the mantle that accommodates both the lateral and the vertical motions of the overlying lithosphere.

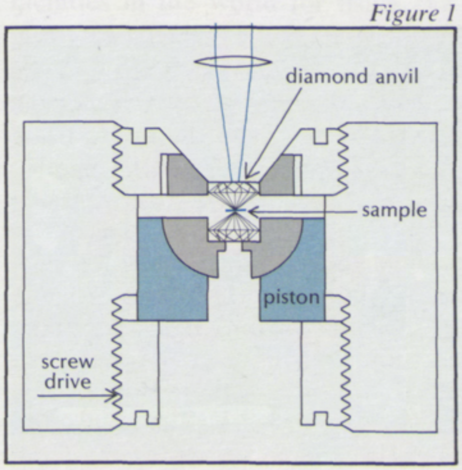
The core is known to be liquid from approximately 2,900 to approximately 5,200 kilometers, and solid from there to the center. The magnetic field of the earth originates in the liquid, electrically conducting region. Very little is known about the nature of the solid core. Considerations of the density, pressure-temperature conditions, and magnetic field of the earth, and the cosmological abundances of the elements, all suggest that the core of Earth is predominantly iron, with perhaps several percent of other elements such as nickel, silicon, oxygen, carbon, and sulfur.

Figure 1. Laser heating in the diamond-anvil cell. Laser radiation is focused onto the sample, which is squeezed between two diamond anvils. The anvils are mounted on the ends of pistons that are driven together by a screw-drive.

IS THERE LIQUID CARBON IN THE INTERIOR?

Because carbon is a common element in the solar system and presumably occurs within the mantle and core, its properties there may have an important influence on the nature of the interior. This influence could be significant if carbon is a liquid under the high-pressure and high-temperature conditions of the mantle—and there is reason to believe that this may be so. It has been suggested (by Francis Bundy in 1963) that diamond, like ice, has a melting temperature that decreases with increasing pressure. The main objective of our research is to determine whether the melting temperature of diamond does, indeed, decrease with pressure, and if so, whether carbon might be a liquid below some depth within the earth.

Figure 1



To achieve the very high pressures needed for such experiments, we "squeeze" our samples between two flat faces of single-crystal diamonds in a diamond-anvil cell (Figure 1). To achieve very high temperatures, we focus infrared radiation from a rapidly pulsed, Q-switched YAG laser through one of the diamond anvils onto the sample.

In one of our experiments, with a sample consisting of graphite powder mixed with potassium bromide, we found evidence of melting (see Figure 2). During the experiment, the focused laser beam damaged one of the anvil faces, producing a "streak" with two

Figure 2a

b

c

Figure 2. Possible evidence of the melting of diamond.

A damage streak that appeared on the surface of one of the diamond anvils during an experiment is shown in a, *a photograph taken with an optical microscope. The portion of the streak area that was at lower pressure during heating is opaque, indicating that it consists of graphite. The portion that was at higher pressure is transparent, indicating that it consists of diamond and/or quenched diamond-melt. (The bar scale = 40 micrometers.)*

The image in b, *obtained with a scanning electron microscope, shows the transparent portion of the damage streak. A back-scattered imaging mode was used to emphasize topography. The low-pressure portion of the streak has a raised surface, but in the high-pressure portion there is a groove with ridges on each side; this is interpreted as diamond that had been melted. (The bar scale = 30 micrometers.)*

A detail of the "furrow" produced by melting of the surface of the diamond anvil is shown in c. *The small arcuate ridges that run across the "furrow" are known to be caused by the pulses of the Q-switched laser used to heat the sample. The small, bright, circular "dots" are droplets of potassium bromide, which was the pressure medium used in the experiment. Some of these "dots" are imbedded within the diamond. (The bar scale = 12 micrometers.)*

distinct parts: an opaque portion in a relatively low-pressure region, and a transparent portion in a high-pressure region (Figure 2a). Our interpretation is that the two portions of the streak consist of graphite and diamond. Scanning electron microscopy (Figure 2b) showed that the region that was at high pressure has a groove with ridges on each side, suggestive of melting. Some of the scanning electron images of the furrow (Figure 2c) show small "dots," which we identified as potassium bromide. Some of these dots remained even after washing, and a subsequent stereopair of scanning electron images showed that they are beneath the surface of the transparent carbon in the furrow. An analysis of the imbedded material confirmed that these dots, too, are potassium bromide. The indication is that droplets of potassium bromide had been enveloped by liquid carbon.

The next step in this investigation will be to measure temperature during the time of diamond melting. We are developing a system that will give a spectrum of the incandescent light from the heated sample during a twenty-nanosecond interval. From this spectrum it will be possible to determine the temperature on the basis of a quasi-black-body emission. The shortness of the time interval needed to acquire the spectrum will permit us to measure temperatures produced during individual pulses of the Q-switched laser, thus avoiding fluctuations from one pulse to the next.

If we find that the melting temperature of diamond does decrease with increasing pressure, there will be good reason to conclude that liquid carbon exists within the earth's mantle. If present in sufficient quantities, liquid carbon could be important as a lubricant for mantle convection. Also, liquid carbon could provide a driving mechanism for mantle plumes, which are responsible for such features as the Hawaiian volcanoes.

SYNCHROTRON X-RAYS FOR PHASE TRANSITION STUDIES

The high pressure produced in a diamond cell can also be used to study phase transitions in mantle materials. In the Cornell project, the first sample to be studied by this technique was fayalite (Fe_2SiO_4), which undergoes a pressure-induced transition from the olivine structure to the spinel structure at a temperature of several hundred degrees. Under an optical microscope, the transition can be observed as a change in color, but visual observations do not yield crystallographic information; x-ray diffraction is necessary for that.

A serious experimental problem with using x-rays from a conventional source is that the measurements take a long time: obtaining even one diffraction pattern requires days, and observing a phase transition in progress would take the better part of a year. Until the very intense x-rays from synchrotron sources became available, an experiment like that simply could not be considered. We are fortunate to have here at Cornell one of the best facilities in the world for using synchrotron radiation. The Cornell High Energy Synchrotron Source (CHESS) at the Wilson Laboratory produces an x-ray beam so much stronger than those from conventional sources that a diffraction pattern can be obtained in just one minute. With this capability, it is entirely feasible to examine a phase transition in progress within the diamond-anvil cell.

Our interest in the olivine-spinel transition derives from a suggestion made by Jean Paul Poirier in 1981. He pointed out that the two structures differ in the way the oxygen atoms are stacked and in the distribution of cations in the interstices, and he suggested that the transition mechanism depends on a restacking of the oxygen atoms and a redistribution of the metal atoms. We reasoned that there might be a time interval between these two proposed processes, and that during such an interval a sample should produce an x-ray diffraction pattern different from that of either the low-pressure or the high-pressure phase.

In our experimental set-up (Figure 3), x-rays scattered by the sample are detected and the energies of the emerging photons are analyzed and displayed on an oscilloscope. The resulting pattern is used to determine crystallographic information about the sample. The intensity of the x-ray beam is so great that the runs must be made inside a closed, lead-lined cave, and changes in pressure and temperature in the diamond cell must be made by remote control. One minute is required to increase pressure or temperature, and one minute is required to obtain a diffraction pattern and store it on a floppy

Figure 3

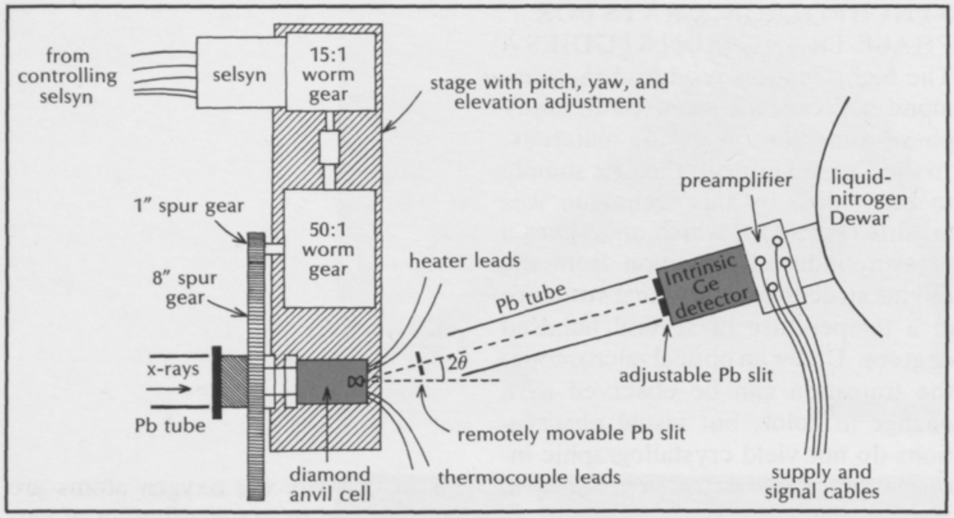


Figure 3. Schematic diagram showing the arrangement of the diamond-anvil cell in the x-ray beam from the Cornell High Energy Synchrotron Source (CHESS). A white beam of x-rays (that is, one containing a large range of wavelengths) is collimated so as to pass through one of the diamond anvils to reach the sample. Information about the atomic arrangement within the sample at high temperature and pressure is obtained from scattered x-rays picked up by the germanium detector.

The experiment must be run inside a lead-lined "cave"; pressure and temperature inside the cell are remotely controlled. Pressure is applied to the sample by a driver turned by means of a selsyn motor and gear system, and temperature is adjusted by means of heating elements attached to a variable transformer outside the cave. Changes in pressure and temperature can be made without turning off the x-ray beam.

disk. In a typical running period of three to four hours, we can easily obtain a series of patterns at small increments of time as the sample passes through a phase transition.

We made several series of runs in which we set the temperature and changed the pressure, and at 500°C we observed the phenomenon we were looking for: one pattern clearly showed the diffraction peaks expected for the intermediate state in which the oxygen atoms had become restacked but the metal atoms were not yet reordered. Next we made a run at a somewhat lower temperature and quenched the sample as soon as the transition began to occur. A diffraction pattern of this sample, obtained with use of a more sensitive photographic technique, confirmed the existence of the intermediate stage.

Our experiments show that Poirier's suggested mechanism is correct, at least for the conditions that exist within the diamond cell, where intense shearing takes place. In a more uniform, isotropic environment, there is probably a different mechanism, one of nucleation and growth. Such a mechanism would have a higher kinetic barrier—that is, a greater overpressure or a higher temperature would be required to make the transition take place. Further measurements should help us understand this better.

Knowledge of the phase transition between olivine and spinel will increase significantly our understanding of mantle processes. It is generally agreed that this transition is responsible for the seismic discontinuity (a change in seismic wave velocity) observed at a depth of about 400 kilometers. It has been suggested that very deep-seated earthquakes may result from an abrupt triggering of this transition as lithosphere descends across the discontinuity in a subduction zone. In such a process, olivine in the subducting lithosphere might pass metastably into conditions under which the spinel structure is actually the stable phase; any shear stress, however, could trigger the transition because it would lower the kinetic barrier. Once the transition started, it would propagate through the metastable olivine because the transition itself would generate shear stresses which in turn would cause nearby olivine to transform.

STUDIES OF MINERALS DERIVED FROM THE MANTLE

In the third Cornell study of the earth's interior, we are examining mantle rocks and minerals that have been brought to the surface by natural processes. Volcanic processes are known to transport mantle material to the surface; an example is kimberlite, the source of diamond, which can be

Figure 4

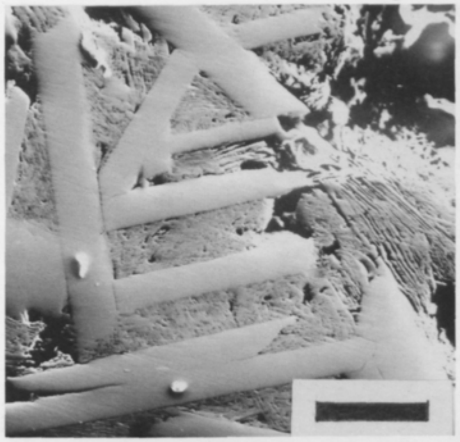
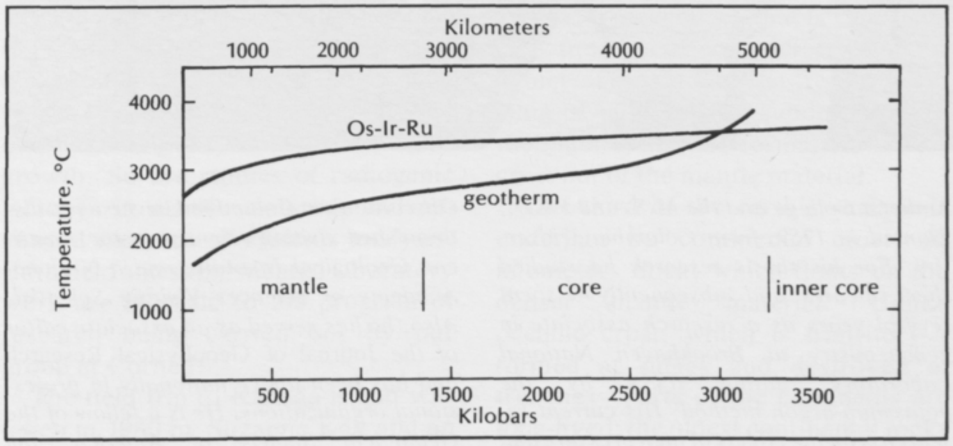


Figure 4. A scanning electron micrograph of a naturally occurring Os-Ir-Ru alloy specimen found in Oregon and believed to have originated deep in the earth's interior. Intergrown laths of osmium-rich metal occur in a fine matrix of iridium-rich metal. (The bar scale = 50 micrometers.)

Figure 5. A plot showing the melting temperature of Os-Ir-Ru alloys, compared with the temperature distribution within the earth. The inference is that the minerals might have been formed close to the inner core.

Figure 5

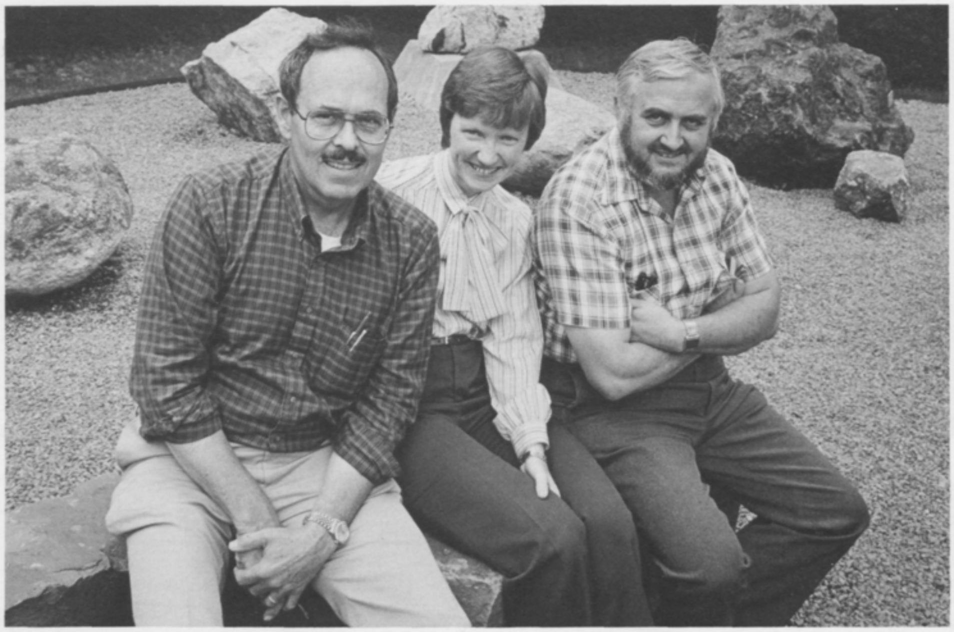


erupted from depths as great as several hundreds of kilometers. Although it is generally believed that the deep interior is completely inaccessible to sampling, we have been working for a number of years on rocks and minerals that we believe may have been transported by convection and volcanism from great depths.

These rocks and minerals include complex assemblages of iron-titanium oxides, platinum-group alloys, carbides, and iron-nickel alloys. They are usually associated with mantle rocks of the lithosphere (known as ophiolites) that have been brought to the surface by plate tectonic processes or by volcanic eruptions. These specimens are exceedingly rare. They have been formed at, or affected by, temperatures and pressures very much higher than those of the lithosphere, and they are usually very inert to chemical change on the earth's surface. We are interested in determining the physical and chemical conditions under which these various rocks and minerals were formed.

One rock that is of particular interest to us is an assemblage of osmium-iridium-ruthenium alloys. Specimens, very rare, are found in gold and platinum placer deposits that form by erosion of surface exposures of mantle rocks of the lithosphere. Figure 4, a scanning electron microscope image of one of these assemblages, shows metal laths that are rich in osmium and a finer surrounding matrix of iridium-rich metal. The actual geologic process by which this assemblage was formed remains unknown, but metallurgical studies show that upon cooling of a melt of Os-Ir, the laths would form first and then the matrix would crystallize. The temperature at which this would happen is in the approximate range of 3,000 to 2,500° C, so that if the specimen shown in Figure 4 cooled from a melt, it must have come from the deep interior where such high temperatures exist, or else it must have been produced by some unknown process in the upper mantle or lithosphere. A plot (Figure 5) of the extrapolated melting temperature of this alloy and of the model temperature, or

Right: The authors pose in Cornell's rock park developed by the Department of Geological Sciences. From the left are John M. Bird, Maura S. Weathers, and William A. Bassett.



geotherm, of Earth indicates that there are no known temperatures outside the core that are sufficient to melt these alloys.

FINDING WAYS TO EXPLORE AT DEPTH

The three projects described here demonstrate that there are ways of studying the seemingly inaccessible regions of Earth's interior. Finding out how minerals behave under pressure and temperature conditions far beneath the crust is one approach. Following this route, investigators can reach a better understanding of the processes taking place below. Another way is to examine actual rock specimens transported by natural processes to the surface from the mantle or, perhaps, even from the core.

In some ways, exploring the depths of our planet is a more formidable challenge than exploring the depths of space. Yet ingenuity in finding and interpreting clues can help us study depths we cannot enter. The earth's interior may not be so inaccessible after all.

Professors William A. Bassett and John M. Bird, and Senior Research Associate Maura S. Weathers are in the Department of Geological Sciences.

Bassett joined the Cornell faculty in 1978 after sixteen years at the University of Rochester. He holds the B.A. degree from Amherst College and the M.S. and Ph.D., granted in 1959, from Columbia University. For his thesis research he studied sheet silicates, and subsequently he spent several years as a research associate in geochemistry at Brookhaven National Laboratory, dating rocks by the potassium-argon method. His current research is on the effects of high pressure and high temperature on the properties and phase relationships of minerals. He is a fellow of the American Geophysical Union, the Geological Society of America, and the Mineralogical Society of America.

Bird came to Cornell in 1972 from the State University of New York at Albany, where he was chairman of the geological sciences department. He received his undergraduate education at Union College and did his graduate work at Rensselaer Polytechnic Institute, earning the Ph.D. in 1959. A specialist in geotectonics, orogeny, and the origin of terrestrial metals, he has been a senior research associate at the Lamont-Doherty Geological Observatory at Columbia University, a distinguished visiting scientist at the American Geological Institute, and a National Academy of Sciences Visiting Scientist. Also, he has served as an associate editor of the Journal of Geophysical Research *and has been active nationally in professional organizations. He is a fellow of the Geological Society of America, the Geological Society of Canada, and the Explorers' Club.*

Weathers holds three degrees in geology from Cornell and has worked in the department since receiving the doctorate in 1978. Her specialties are structural geology and microstructures; among her contributions has been the development of scanning transmission electron microscope techniques for geological applications. In addition to laboratory research, she has done field work, including mapping and sample collecting, in the western United States, Newfoundland, Greenland, Scotland, Ireland, West Germany, and the Italian and Swiss Alps.

THE GROWTH OF CONTINENTAL CRUST

by Robert W. Kay and Suzanne Mahlburg Kay

A helicopter ride across a foggy strait in the Aleutians for two days of rock collecting on an uninhabited island was part of the agenda for current research on chemical geodynamics and crustal growth. So are studies of radiogenic isotopes in mantle material, and advanced methods of systems analysis. Both field and sophisticated laboratory work are intrinsic to the program of research being carried out by our group at Cornell.

The field trip to Kanaga island was taken in 1980 by Suzanne Kay and an undergraduate associate, Kurt Dodd. The trip yielded a collection of rock samples that proved to be very important to the overall investigation, and it illustrates another ingredient of geological research: luck and persistence in finding useful or essential evidence. Over the thirteen years the project has been going, the field work has taken researchers to the Philippines and the Argentine Andes, as well as the Aleutians.

What we are studying is the vast geotectonic cycle linking continents, oceans, volcanoes, and the underlying mantle: a mechanism that is surely the most fundamental characteristic of our planet. The net results are the recycling of old crust by subduction into the mantle, and the formation of new crust out of the mantle material.

One-third of the earth's surface is underlain by continental crust, 35 kilometers thick, which floats on the denser mantle material. Unlike oceanic crust, which is transitory—formed at ridges and destroyed at trenches—parts of the continents are long-lived: the oldest continental rocks have existed in a crystallized state for more than four billion years.

Our studies seek answers to some elementary questions: How does the continental crust form? Once it forms, is some of it destroyed, as oceanic crust is, by being returned to the mantle? If so, what is the mechanism and what are the rates of formation and destruction through geologic time? Our approach is to establish mass fluxes in the geotectonic system of the present earth. To quantify continental growth, we are examining the two complementary reservoirs—the crust and the mantle—using the techniques of phase equilibrium and trace-element and isotopic geochemistry, and the methodology of systems analysis. Since new crust appears at the surface as magmatic island arcs, much of our field work is carried out at those locations.

CRUSTAL GROWTH DEDUCED FROM MANTLE CHEMISTRY

If depleted mantle and crust are strictly complementary in a system such as the one depicted in Figure 1, they must share a common geochemical history, and therefore the evolution of radiogenic isotopes from the mantle can be used to calculate the history of crustal growth. This may seem a perverse way to approach crustal evolution, but actually the mantle offers the advantage of being much more homogeneous than the crust because of convective mixing. It is not as inaccessible as it might seem, either, because mantle material frequently undergoes partial melting, yielding basalt, and basalts with ages spanning most of the earth's history are fre-

Figure 1

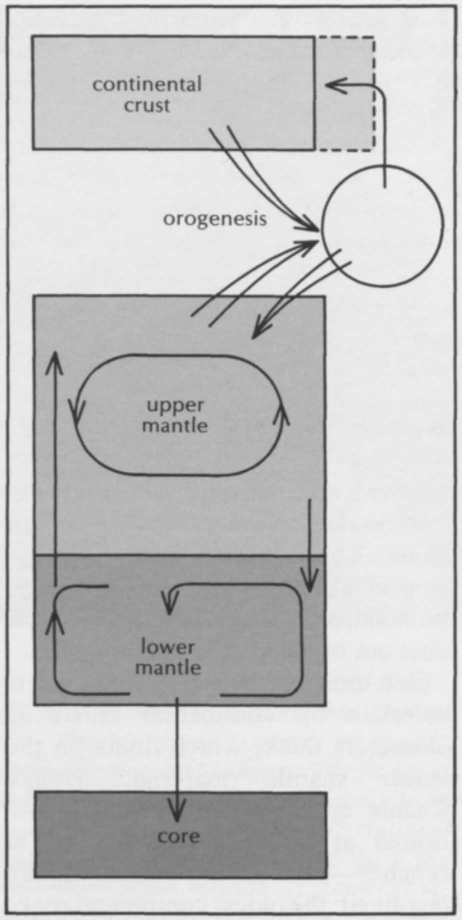


Figure 1. Box model showing mass transfer between the earth's rock reservoirs. The Orogenesis circle represents the interface between crust and mantle at localities like the Aleutian Islands, the Philippines, and the Andes.

Figure 2a

2b

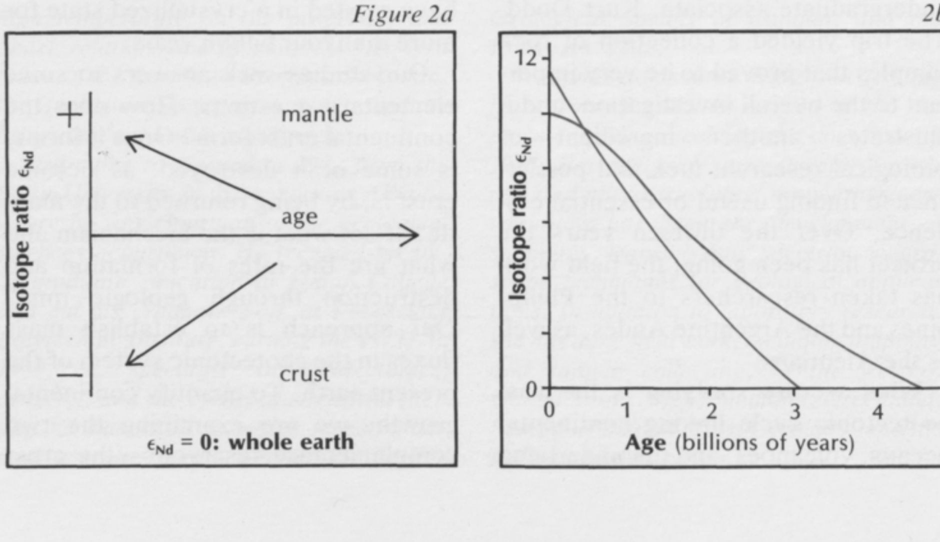


Figure 2. The history of radiogenic isotopes in the mantle, used to calculate crustal growth. Extraction of crust from the mantle, as in volcanism, is accompanied by chemical fractionation of elements, and as a result, the ratios of isotopes are different in the crust and in the mantle. The ratio $^{143}Nd/^{144}Nd$, for example, is higher in the mantle. This ratio may be expressed as ϵ_{Nd}, parts per 10^4 deviation from a whole-earth value, taken as 0.

The schematic diagram in a *illustrates the divergence of ϵ_{Nd} in the upper mantle and in the crust as a function of geologic age. The mean crust has a negative value.*

The curves in b *represent two estimates of how ϵ_{Nd} for the upper mantle has changed over the course of the earth's history. This is a hotly debated topic at the present time.*

quently preserved in the geologic record.

CALCULATING CRUSTAL MASS OVER TIME

In the work with radiogenic isotopes, the useful parent species are those with long half-lives: isotopes of rubidium (Rb), samarium (Sm), uranium (U), thorium (Th), lutetium (Lu), rhenium (Re), and potassium (K). For example, the decay of ^{147}Sm into ^{143}Nd (neodymium) has a half-life of 106 billion years. Published curves showing the change in ^{143}Nd in the mantle over the past few billion years are shown in Figure 2. Chemical fractionation has caused the parent-daughter ratio (Sm/Nd) and also the isotope ratio $^{143}Nd/^{144}Nd$ (expressed as ϵ_{Nd}) to be higher in the mantle than in the crust. This means that for a one-way transport of material from crust to mantle, we can calculate the crustal mass (actually, the ratio of crustal mass to mantle mass) as a function of time from a curve such as Figure 2 plus estimates of past Nd and Sm concentrations in the mantle.

It is satisfying to note that the general shape of the crustal-growth curve derived in this way indicates that the crust is forming at a much lower rate at present than in the past. Our estimate of the present rate is about half the rate pertaining to the average for the whole of earth history. Other researchers (using methods that are not keyed to isotope evolution) have deduced lower, or even negative, values for the present rate of crustal growth.

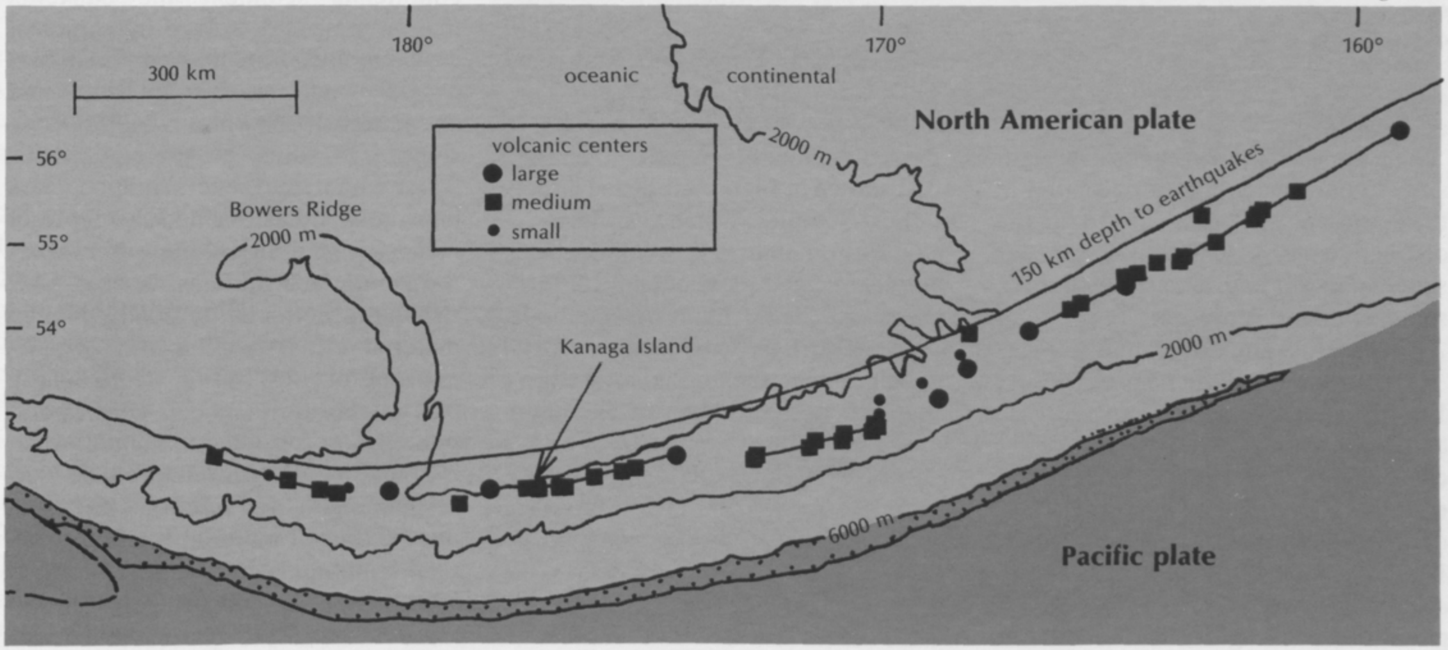
Of course, we have a long way to go in making this systems methodology reliable in applications to processes like crustal-growth rate. A fundamental problem is that the mantle-based model we have outlined so far was developed without regard for magmatic arc processes. In particular, one-way crustal-growth models do not consider the recycling of upper crust back into the mantle during subduction at the arcs, a process for which we now have evidence. Another known process—lower crustal delamination—is also capable of returning crust to the mantle. What is needed is an independent evaluation of mass flux at convergent plate margins. Because the present is the only time in Earth history we can directly assess how much crust is returned to the mantle, this evaluation must depend on present-day measurements.

STUDIES IN THE ALEUTIAN ISLAND ARC OF ALASKA

This brings us to our specific program of crustal investigations in the region we have studied most closely: the Aleutian arc. In the Aleutian subduction zone (see Figure 3) we find an excellent example of interaction

Figure 3. The Aleutian arc. The Pacific lithospheric plate to the south plunges beneath the North American plate at the Aleutian trench. Volcanoes sit about 100 kilometers above the descending plate (note the 150-kilometer depth-to-earthquake contour). Some of the volcanoes form line segments; those indicated on the map are, from west to east, the Rat, Andreanof, Four Mountains, and Cold Bay segments. The arcuate region of new continental crust extending west from about 170° has all formed by arc volcanism and plutonism in the past 50 million years. Older continental crust forms the arc basement to the east.

Figure 3



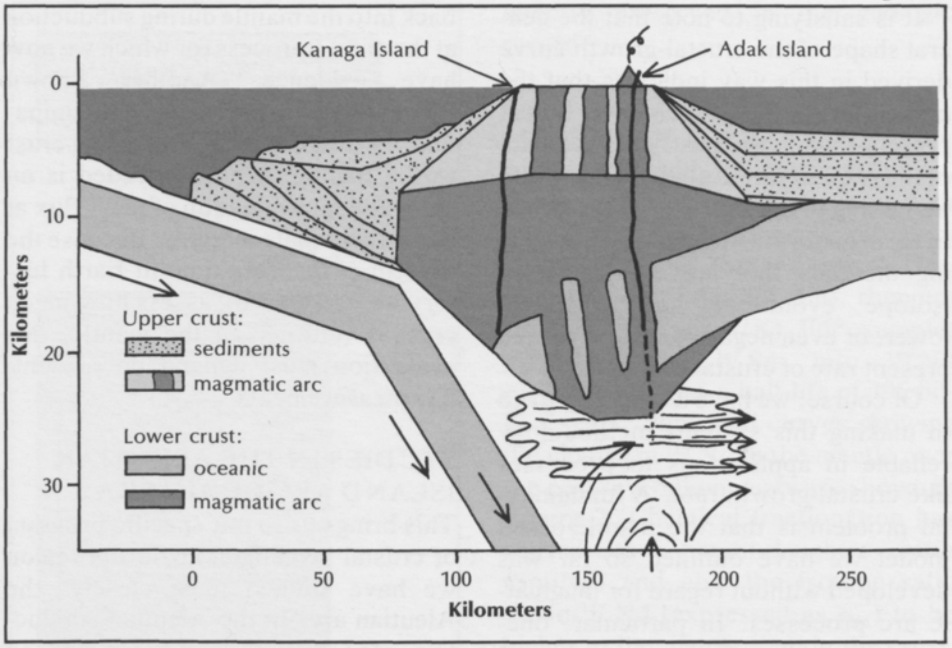


Figure 4. Interpretive cross section of rock types in the Aleutian arc crust. The rock formations in the lower crust and upper mantle were figured out from xenoliths collected on Kanaga Island (see Figure 3) and Adak Island, which is 15 kilometers to the east of Kanaga. The lower crust was found to consist of preexisting oceanic crust plus igneous minerals that settled out of magmas derived from the mantle. (The diagram is adapted from Grow, 1972.)

among volcanoes, continents, oceans, and the mantle.

The two absolutely crucial prerequisites to our evaluation of mass flux in the Aleutians are our ability to tag the distinctive mass reservoirs, and our success in finding a variety of rock samples that represent regions of Aleutian crust and upper mantle.

The tagging is done geochemically. For instance, some samples of volcanic material have the distinctive ϵ_{Nd} of crustal material, and therefore are evidence that part of the continent-derived sedimentary cover of the Pacific oceanic crust is subducted underneath Aleutian volcanoes. In regard to assembling a collection of samples, our good fortune in finding a virtual treasure on the island of Kanaga has been mentioned already. We recovered several hundred crystalline rock fragments that had been ripped by ascending lava from the conduit wall at depths of up to 30 kilometers. The lithologic section of Aleutian crust shown in Figure 4 is based largely on these samples, called *xenoliths*.

These and other representative rock samples, tagged by geochemical techniques and dated by K-Ar methods, have enabled us to calculate crustal growth rates in the arc. Also, we have identified a recycled crustal component in Aleutian arc magmas. We have shown that the subduction process establishes the mass-transfer interface connecting oceans, continents, and the mantle.

A simplified description of the cycle of subduction and crustal formation begins with the descent of one edge of an oceanic plate. Carried along are continental sediment and elements that have been dissolved by chemical erosion of continents and fixed into basaltic oceanic crust by hydrothermal circulation of sea water at mid-oceanic ridges. This subducted material carries water with it, and several million years later, after it has reached the depth of magmatic generation, the water fluxes the mantle and initiates its rise. As it rises, the softened, partially molten material releases arc magmas.

From this description we see that a part of the arc magmas, which comprise newly formed continental crust, is actually older continent crust. Correspondingly, a fraction of the subducted crustal material is added back to the mantle, where it stays for billions of years and becomes mixed with the total mass by convection. This

Photos taken by Cornell researchers show scenes from field work in the Aleutians. Above: On an early trip to Kanaga Island, Hannes Brueckner (a Cornell graduate, now a professor at Queens College, CUNY) poses (at left) with Robert and Suzanne Kay. Right: A field camp on Kagalaska Island. Below: Robert Kay on a high point within the plutonic exposure on Adak Island.

recycled crust is an important factor in our calculations of mass fluxes, for it adds a term in the equation for isotopic growth of ^{143}Nd in the mantle.

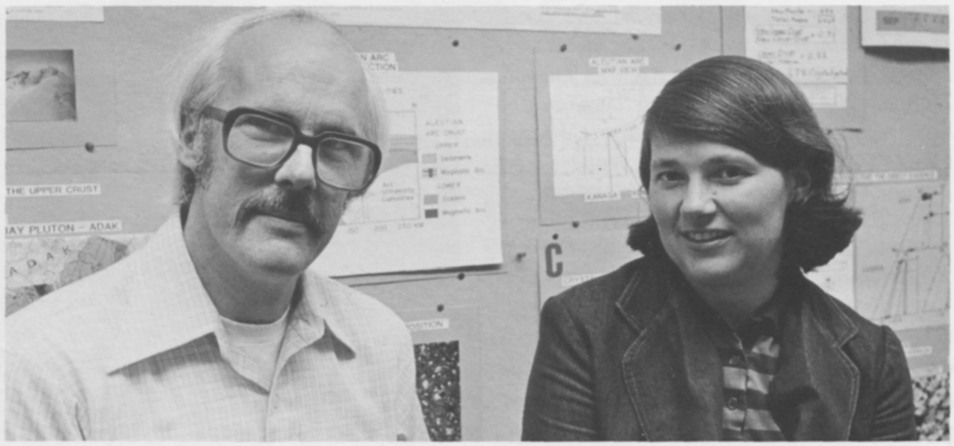
A COMMON FOCUS IN A BROAD PROGRAM

The Aleutian studies are complemented by projects that are widely dispersed geographically, but have a common focus: the investigation of the recycling of continental crust. We go to the Philippines and the Andes because they too are volcanic arcs. An interesting feature in the Philippines, for example, is the Zambales Ophiolite, a piece of oceanic crust now exposed on land. In the Andes, our investigation centers on the relationship

"Both field and sophisticated laboratory work are intrinsic to the program of research. . ."

between magma type and regional tectonics in a region of unusually thick continental crust; it is part of a collaborative project by researchers from Cornell and other institutions.

Quantifying crustal recycling is a long-term effort that requires a variety of approaches and techniques. Computers, mass spectrometers, electron microprobes, and x-ray and neutron-activation facilities are among the tools we use; so are camping gear, field boots, and compasses. Our project illustrates the combination of field and laboratory work, and of observation and theory, that characterizes modern research in the geological sciences.



Robert W. Kay, associate professor of geological sciences, joined the Cornell faculty in 1976. Suzanne Mahlburg Kay is a senior research associate.

Robert W. Kay was educated at Brown University, which awarded him the A.B. degree in 1964, and at Columbia University, where he earned the Ph.D. in 1970. He taught at Columbia for five years and was a research geophysicist at the University of California at Los Angeles for a year before coming to Cornell. In 1982-83 he served as a visiting associate at the California Institute of Technology, and since 1979 he has been associated with the United States Geological Survey, Menlo Park, California.

He is a fellow of the Geological Society of America and a member of the Geochemical Society, the American Geophysical Union, the International Association of Geochemistry and Cosmochemistry, and the International Association of Volcanology and the Study of the Earth's Interior.

Suzanne Mahlburg Kay studied at the University of Illinois at Urbana-Champaign for her B.S. and M.S. degrees, and received the Ph.D. from Brown University in 1975. She was a postdoctoral fellow and taught at the University of California at Los Angeles before coming to Cornell in 1976. Since then she has served as an instructor at the University of Illinois summer geology field camp and as a visiting associate in petrology at the California Institute of Technology.

She is a member of the American Geophysical Union, the Geological Society of America, the Mineralogical Society of America, the Mineralogical Society of Canada, and Sigma Xi.

UNANSWERED QUESTIONS ABOUT FINGER LAKES GEOMORPHOLOGY

by Arthur L. Bloom

The Finger Lakes region is a truly classic area for geologic research. The Devonian System of the geologic column, named for the rocks in Devonshire, England, might easily have been called the Erian System, after Lake Erie, had not Dr. James Hall and his colleagues at the early New York State Geological Survey been beaten into print by members of the British Geological Survey in 1839.

The rocks in Devonshire are badly disturbed and faulted, so that despite the nomenclature, the best place to study Devonian rocks is central New York. The gently tilted 6,000-foot pile of Devonian strata and their belted east-west exposures across the state, combined with the deep north-to-south Finger Lakes valleys and innumerable gorges, offer ideal exposures for systematic study of the rocks and their fossils. One could say that the book is laid open here with the somewhat time-worn pages separated, to be read by anyone who knows the language.

Right: Gorge walls along Fall Creek near Cornell provide ideal rock exposures.

“. . .the best place to study Devonian rocks is central New York.”

A GAP IN THE REGIONAL GEOLOGIC HISTORY

The excellent exposures of Devonian rocks in the Finger Lakes region are largely the work of subaerial river erosion and the multiple continental glaciers of the Pleistocene Epoch during the last two million years or so. From the end of the Devonian Period, 360 million years ago, until late in the last ice age about 50,000 years ago, our regional geologic history is essentially blank, wiped out by rivers and glaciers.

We know that the rise of the Appalachian Mountains, already in progress in the Devonian period, culminated about 100 million years later in the final closing of the Atlantic Ocean basin, with western Europe and northwestern Africa tightly fused to eastern North America. It is no accident that the European immigrant geologists in the United States recognized the rocks here and gave them European names. This was the other half of the same pile of rocks that they had studied for several centuries.

Opposite: This satellite image of the snow-dusted Finger Lakes area clearly shows features of the geomorphology of the region. The lakes are believed to be glacial troughs formed from river valleys. Note the Y shape of the northern end of Keuka Lake; this is interpreted as evidence of an ancient southward flow of rivers that was later reversed.

Right: This aerial view of Cayuga Lake, the Finger Lake below Cornell University, suggests an earlier existence as a river valley.

We also know that when the present Atlantic Ocean began to open about 200 million years ago, the Finger Lakes region was gently uplifted. The Devonian and related rocks, which had been deposited as mud and sand on a shallow ocean floor but had been converted to rock by the heat and pressure of the Appalachian Mountain building, were exposed to subaerial erosion that continues today. From the volume of the great sedimentary pile on the present North American Atlantic continental shelf, it has been reliably estimated that in the last 65 million years eastern North America has had about two kilometers of rock eroded away by rivers and glaciers and redeposited in the ocean. The long-term average rate of erosion, about 3 centimeters per 1,000 years, corresponds to the typical rate of river erosion—as measured by the annual sediment load—for the forested eastern United States.

What happened to the Finger Lakes region during this enormous time of erosion? The pile of rocks had been tilted southward during mountain building: to the north, the Canadian shield (ancient granites and metamorphic rocks of the continental crust) and probably the Adirondack highlands had been uplifted. We hypothesize that rivers in this region flowed southward down the regional dip of the strata, somewhat in the pattern of the present Delaware and Susquehanna Rivers. Traces of the ancient drainage may be seen today in the upper parts of the Fall Creek, Salmon Creek, and Tioghnioga River systems northeast of Ithaca, and in the south-pointing "Y" shape of Keuka Lake. This ancestral southerly drainage was at a much higher level than the modern landscape—perhaps 1,000 feet above the Cornell campus.

Then, some time in the last 25 million years, and perhaps "only" in the last few million years, the Finger Lakes region was raised again by perhaps 2,000 feet. Newly invigorated streams carved deeper valleys. In particular, on the northward-sloping hillsides eroded on the upturned edges of the Devonian strata in central New

Figure 1

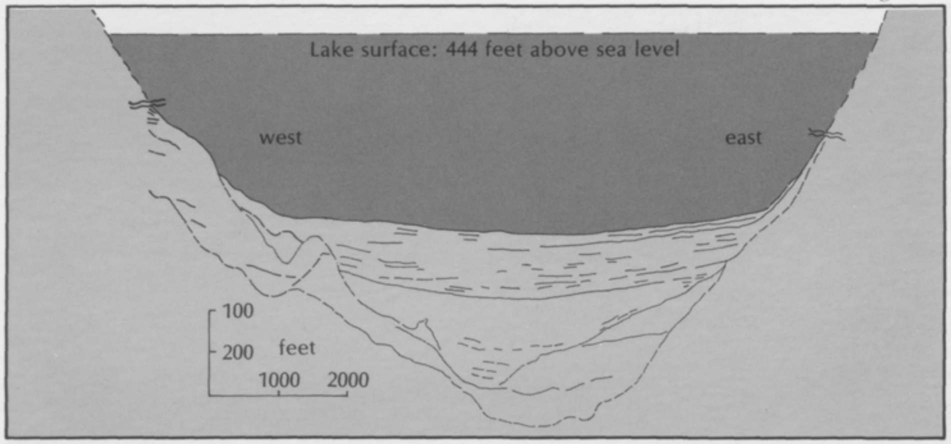


Figure 1. A seismic reflection profile of Seneca Lake, based on data from a study for the Naval Research Laboratory. Although the topmost layer of muddy deposits is U-shaped, the morphology expected for a glacially carved valley, the rock bottom appears more V-shaped, like a river valley. The maximum depth of the lake along the trace is 475 feet, so that the mud bottom is 31 feet below sea level. The deep reflections are from layers at least 500 feet below the present sea level. (This figure is adapted from a trace prepared by C. C. Windisch of the Lamont-Doherty Geological Observatory, and subsequently published by D. L. Woodrow, T. R. Blackburn, and E. C. Monahan in the 1969 Proceedings of 12th Conference on Great Lakes Research.*)*

York, a new generation of north-flowing streams carved deep, narrow valleys into the northern edge of the Appalachian (or Allegheny) Plateau. These energetic rivers eroded headward and southward into the plateau and captured, or diverted northward, the upstream tributaries that formerly drained south. Similar uplift and entrenchment in relatively recent geologic time created similar drainage diversions as far west as Ohio, at least. Why should a continental platform, stable for 200 million years, suddenly rise a few hundred or a few thousand feet? Is the uplift continuing today? These questions of vertical *epeirogenic* (continental-scale) tectonics have yet to be answered. Certainly the Cornell program for the study of the continental crust will shed new light on this old problem.

EFFECTS OF GLACIATION ON LOCAL GEOGRAPHY

During the last two million years, at least twenty ice ages have gripped the earth. We are now in one of the relatively brief interglacial intervals; we have no reason to believe that the age of ice sheets is over.

Today, 10 percent of the earth's land surface is ice-covered; during periods of full glaciation, as much as 30 percent of the land was under ice. In eastern North America snow accumulated, compressed to ice, and spread southward as far as the line from Williamsport, Pennsylvania, to Princeton, New Jersey. According to our best modeling of modern ice sheets, Ithaca would have been repeatedly buried by more than a mile and a half of ice during such times. Our highest hills were only rough places on the underside of the ice sheet.

In the late 1890s and early 1900s a Cornell geology professor, Ralph Stockman Tarr, was a leader in the study of glaciers and glacial erosion. His expedition to Greenland and several expeditions to Alaska alternated with his research on the origin of the Finger Lakes. In an early paper, "Cayuga Lake; a Rock Basin," Tarr suggested that the process chiefly responsible for forming the lakes was glacial erosion, which converted river valleys into glacial troughs (closed basins eroded into the bedrock with rock rims at each side). Tarr and his students soon learned that most of the erosion had predated the most recent ice age (in Tarr's time only four ice ages were recognized). They joined the vigorous debate that was in progress at the time as to whether glaciers eroded the land or protected it from river erosion, and in a later series of papers, Tarr expressed doubt that glacial erosion could have shaped the valleys of the Finger Lakes without more greatly modifying the hilltops and smaller valleys of the region. Before his tragically early death in 1912, he once again came to consider intense glacial erosion as the cause of the Finger Lakes troughs.

WHY ARE THE FINGER LAKES SO DEEP?

Tarr and his contemporaries knew that the bottoms of the lakes were muddy deposits and not smooth, eroded rock.

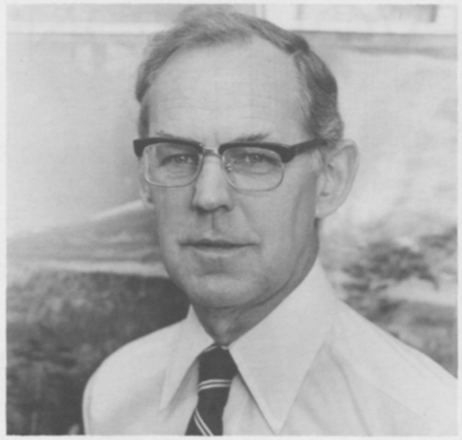
They had no means of sounding the layers of accumulated mud to determine the true depth and shape of the inferred glacially eroded rock basin. It was known that even the mud bottoms of the two large lakes were below sea level—Seneca Lake at –174 feet and Cayuga Lake at –36 feet.

Today we have available the seismic reflection profiling technique for mapping deep layers. The only profile that has been published so far is one of Seneca Lake (Figure 1). Although it lacks detail—the primary data, collected by a United States Navy sonar test facility, have not been released—this figure shows some clearly defined features and raises numerous questions about Seneca Lake and the Finger Lakes in general. The mud bottom defines the smooth catenary or U-shaped cross section typical of a glaciated valley. But what are the layers beneath? Multiple erosional and depositional events are indicated, for younger layers truncate or bury older ones. Was the valley eroded by many glacial advances? If so, not all of the older sedimentary deposits were removed during later ice ages. Were one or more of the earlier ice sheets more "aggressive" in eroding the Seneca Lake trough? If so, why?

The most intriguing feature of all is the shape of the inferred rock floor basin, under the layers of sediment; it does not look at all like a U-shaped glacial trough, but rather like a rugged, V-shaped river valley. This presents a problem, since the rock floor is at least 500 feet deeper than the mud bottom and therefore far below sea level. If the valley was cut by a river with an outlet to the ocean, how can this be explained? Has the ocean risen since, or has the land subsided, in spite of the earlier uplift? Longitudinal seismic profiles of Seneca and Cayuga Lakes, tied to appropriate cross-profiles such as Figure 1, might reveal a barely suspected missing chapter in the history of the Finger Lakes region.

When were our uplands eroded? Was the region eroded to a flat plain near sea level and then rejuvenated? If so, when did this happen? Was the uplift gradual and continuous or intermittent? Is it continuing today? What internal forces cause continental surfaces to be raised without being deformed into mountain ranges? When and by what processes were the great Finger Lakes troughs eroded?

These are a few of the geomorphic questions that may involve Cornell geologists as they work from their new offices and laboratories in Snee Hall. What better location for modern investigations than a region with magnificent gorge exposures of Devonian rocks near deep lakes of uncertain and disputed origin?



Arthur L. Bloom, professor of geological sciences, came to Cornell in 1960 from Yale University, where he earned the doctorate the previous year. He began his education in geology at Miami University, which awarded him the B.A. degree in 1950, and subsequently studied as a Fulbright scholar at Victoria University in New Zealand under the noted geomorphologist Sir Charles Cotton. After four years as an officer in the amphibious forces of the United States Pacific fleet, he continued his graduate study at Yale.

During his years at Cornell, Bloom has spent leaves as a visiting lecturer at Yale; in Australia as a senior Fulbright research scholar at James Cook University and the Australian National University; and as a research fellow of the Japan Society for the Promotion of Science at Kobe University. He has also lectured and shared research projects at Seoul National University, Korea, and the Third Marine Institute, Xiamen, China.

Bloom is a fellow of the American Association for the Advancement of Science and of the Geological Society of America. He is an associate editor of the American Journal of Science *and the* Geological Society of America Bulletin *and on the editorial board of* Quaternary Research.

THE PACE OF EVOLUTION

New Insights from Fossils

by John L. Cisne

Is evolution continual or episodic? Is change in genetic makeup of populations distributed more or less evenly over the history of a lineage, or is it concentrated in occasional short bursts?

Debate over *gradual* versus *punctuated* evolution, as the two concepts (see Figure 1) have come to be known, has attracted lively interest for more than a decade. The gradual view holds that evolution proceeds slowly and steadily, and that species become differentiated through so-called "microevolutionary" processes, observable in natural and laboratory populations. The punctuated view holds that evolution is concentrated in speciation events—sometimes occurring in less than a million years—during which the population that founds a new species becomes genetically isolated from its parent stock. Many proponents of the punctuated view see a qualitative difference between microevolutionary processes and speciation, which is considered a "macroevolutionary" process.

Darwin regarded the fossil record as the ultimate test of his theory of evolution. While it is possible to trace the course of evolution from fossils, in order to resolve the current controversy it is necessary to distinguish between species and recognize speciation. According to the biological definition, a species is a group of actively or potentially interbreeding populations. This definition is impossible to apply in classifying fossils, and paleontologists must make distinctions on the basis of observable morphology. Are the species they recognize more or less arbitrarily defined segments of steadily evolving lineages, as the gradual view would have it, or are they naturally set off from one another by episodes of rapid evolution?

Figure 1

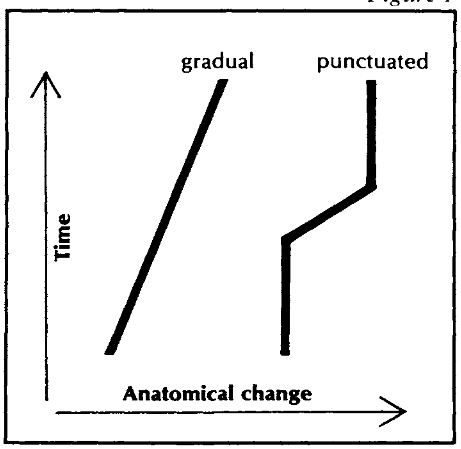


Figure 1. Representations of two current concepts of evolution.

The issue bears not only on our understanding of how life has evolved, but also on how accurately rocks can be dated—and through this, on how precisely geological processes of all sorts can be studied. This is because ages of sedimentary rocks are generally determined from the distribution of fossils; rock that contains a particular fossil must have been laid down sometime between that species' origination and extinction, events that are typically several million years apart. Accordingly, the precision with which fossils can be identified and classified limits the precision of age dating. If the pattern of punctuated evolution is at all common, it promises a way of accurately recognizing species in the fossil record despite problems in attempting to apply the biological species defini-

Figure 2

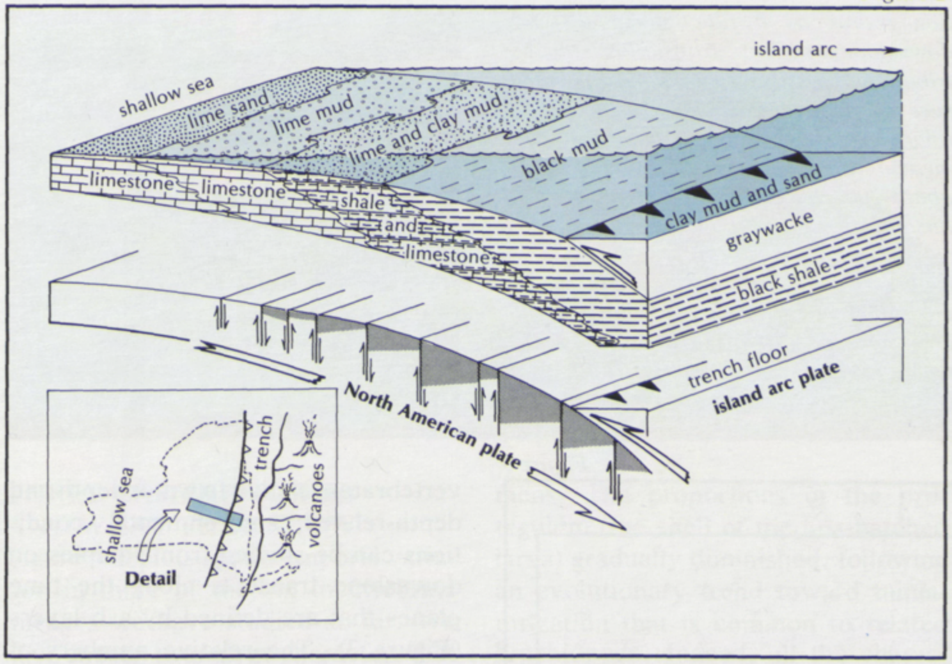


Figure 2. The sedimentary rocks studied in the Cornell project, and their geologic setting. The sediments were laid down about 450 million years ago during the collision of North America with a volcanic island arc that now forms much of New England. Faulting, illustrated in the central sketch, must be taken into account in order to reconstruct the pattern of sedimentation.

tion. And it promises more precise geologic age dating based on geologically short punctuation episodes.

TRACING PATTERNS IN THE FOSSIL RECORD

Precisely documenting the patterns of anatomical and developmental variation in even one lineage takes years of work. The evolutionary patterns diagrammed in Figure 1 are based on only a few dozen detailed studies. My laboratory is perhaps the first to be set up for carrying out such work on a large scale. The studies my students and I are conducting are based on more than 150,000 identified invertebrate fossils from more than 400 thin beds throughout the geologically classic Mohawk Valley area of New York.

Our long-term objective in studying lineage after lineage is to trace the coevolution of the most abundantly represented species. We are synthesizing the evolutionary histories of the lineages in terms of an environment-related gradient: a kind of study never before attempted. We have been able to contribute the first detailed information on geographic as well as temporal variation in lineages. Geographic variation is of interest because it often, though not always, involves change in the genetic makeup of populations. Geographic clines—spatial gradients within species—are of particular interest as direct evidence of short-term adjustment to local environmental conditions, adjustment that is sometimes demonstrably microevolutionary adaptation.

The sediments we are studying (Figure 2) were laid down over a period of roughly five million years on the outer slope of a submarine trench along which North America was colliding with a volcanic island arc that now makes up much of New England. (At that time, the Hudson Valley was similar to the modern Timor Trough, along which Australia is colliding with the Banda island arc.) These strata are especially useful in our studies in three respects:

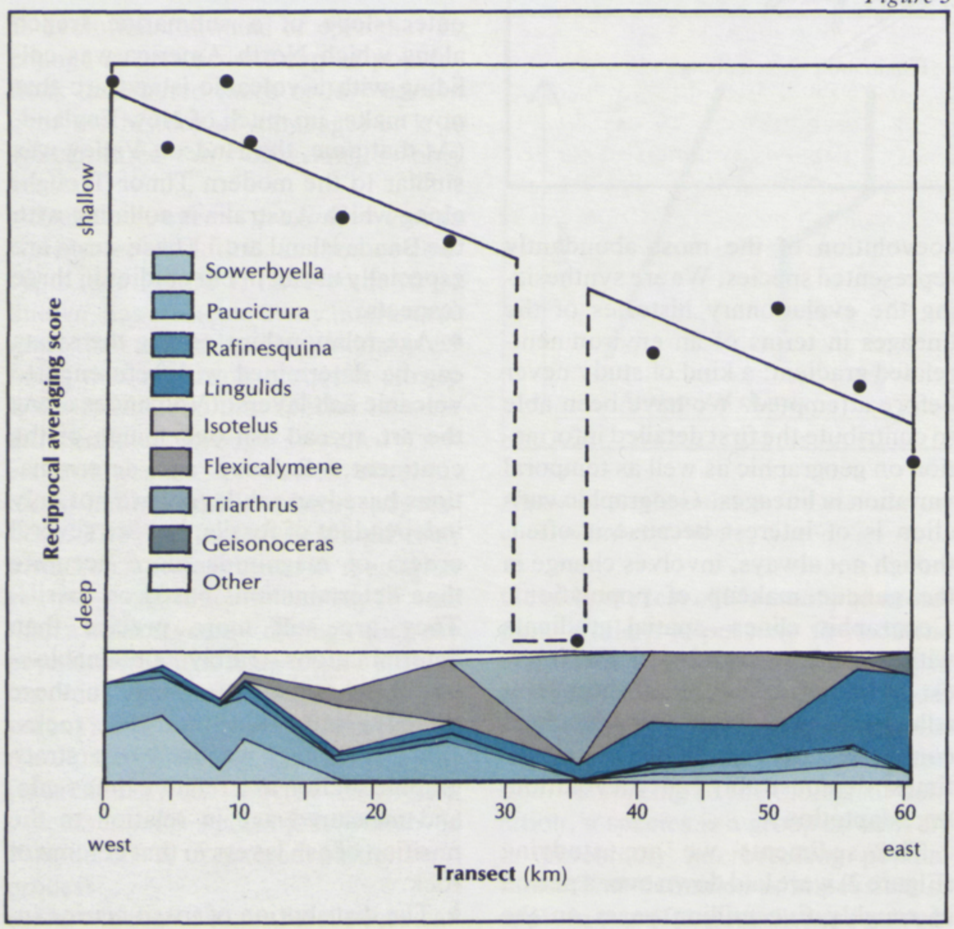
- Age relationships among the strata can be determined with reference to volcanic ash layers. (Volcanoes along the arc spread ash over much of the continent.) Relative age determinations based on ash layers are not only independent of fossils, but are several orders of magnitude more accurate than determinations based on fossils. They are still more precise than determinations—rarely obtainable—based on radioactive decay in these roughly 450-million-year-old rocks. For our study, we used one stratigraphic section as a relative time scale, and measured age in relation to the position of ash layers in that column of rock.
- The distribution of fossil marine in-

Figure 3. The distribution of fossils along the depth gradient (see Figure 2), illustrating how fossils provide a relative measure of water depth. We see here a "depth gauge" calibrated in terms of the relative abundances of certain fossils.

The horizontal panel shows the distribution of species on a downslope transect along one volcanic ash layer. The relative numbers of specimens in different species change steadily downslope with increasing water depth (except in going across a downfaulted block that was a topographic depression at the time). The graph gives the samples' reciprocal averaging ordination scores as a function of distance downslope, in effect "translating" the distribution of fossils into a quantitative measure of relative water depth and depth-related environmental conditions. The measured vertical movement on the faults, about 200 meters, gives a rough idea of absolute depth along the transect.

Right: Volcanic ash layers such as the 1-cm-thick red bentonite indicated by the arrow provide a means of determining relative age relationships among strata. These Ordovician strata are near Newport, New York.

Figure 3



vertebrates relative to water depth and depth-related environmental conditions can be studied from samples on downslope transects along the time planes that are defined by ash layers (Figure 3). The relative numbers of different kinds of bottom-dwelling invertebrates proved to be a reliable "depth gauge" that can be quantitatively calibrated using eigenvector ordination methods perfected by Hugh G. Gauch and his colleagues in Cornell's Section of Ecology and Systematics. The ordination scores of samples provide a general measure of depth-related environmental conditions throughout the whole time interval.

- The combination of a quantitative environmental measure and very precise age determination over distance makes possible precise study of geographic variation, and detection and study of environment-related clines. Given the usual million-year inaccuracy in age determination over distances such as those involved here, geographic variation has been technically difficult to demonstrate and distinguish from temporal variation.

Left: Many complete Flexicalymene *fossils are contained in this slab of rock from a site at Trenton Falls, New York. These fossil specimens represent the species with more abdominal segments that evolved as the trilobite expanded into deeper water.*

Below: The Trenton Falls site, north of Utica, is famous for its well-preserved Ordovician fossils.

THREE CASE HISTORIES AND WHAT THEY SHOW

Figure 4 depicts spatiotemporal variation in three of the six invertebrate lineages we have studied so far. We have chosen to analyze characters that show obvious variation among specimens, and that relate in some way to the organism's presumably genetically controlled pattern of development. The characters we selected have an involvement with growth, for this is important as an indication that spatial and temporal changes are truly evolutionary in the sense that they involve genetic change. (Not all variation has a genetic basis, and anatomical variation in fossils can never be strictly proven to have been genetically based.)

The brachiopod *Leptobolus insignis* seems to show gradual evolution without geographic variation. The shell's daily growth increments record the history of each individual from the time it was a larva swimming in the plankton through its adult life in the mud of the sea floor, and this record of growth enables us to study the larval stage from the fossils of adult specimens. The proportions of the protegulum (the shell of the just-hatched larva) gradually diminished, following an evolutionary trend toward miniaturization that is common to related brachiopods. Indeed, all the characteristics of the later shell that we studied show slow and steady change with time.

In *Triarthrus,* the pattern of development changes gradually over both time and space. There is a tendency for adults to retain particular features that formerly characterized juveniles—an evolutionary pattern called paedomorphosis that is also seen in our own lineage. Through geologic time, adult *Triarthri* tend to retain what was previously the juvenile form of the head. At any given time, individuals living in deeper water also tend to retain the juvenile form of the head. Adult specimens with the "juvenile" head were once distinguished as a separate species, called *Triarthrus eatoni,* while those with the "adult" head were called *Triarthrus becki*. But the overall pattern can now be characterized as a spatiotemporal cline.

In the trilobite *Flexicalymene senaria* we see an example of episodic change. The number of abdominal segments records the pattern in which the segments grew and matured as they were added to the body during larval and juvenile stages. The observed increase with time in the number of segments indicates evolutionary change, but in contrast to what we observed in other lineages, this evolutionary change is confined to a discrete time interval somewhat less than one million years long. This may be an instance of speciation of a kind called parapatric, in which macroevolutionary differentiation takes place by breakdown in interbreeding along a cline. In *Flexicalymene* the ancestral species appears to have become extinct as its descendent expanded into deeper water habitats. Although durations of this and other types of speciation have been estimated only indirectly from studies of modern organisms, the episode's duration is of the order expected for parapatric and other slower speciation modes.

Figure 4

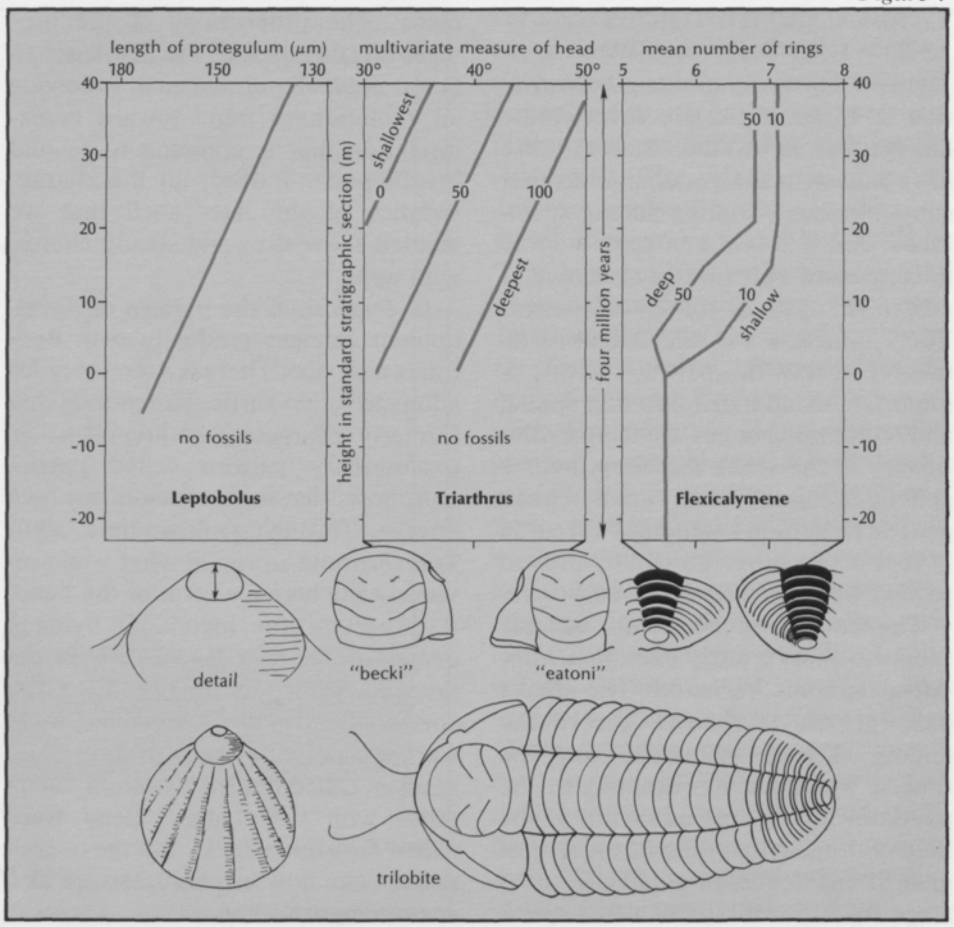


Figure 4. Evolutionary histories of three representative marine invertebrates. Diagrams indicate the nature of evolutionary changes and the appearances of whole fossils. (The brachiopod sometimes reaches 4 millimeters in length. The schematic trilobite with the head of Triarthrus *and tail of* Flexicalymene *would be about 4 centimeters long.)*

The size of the larval shell in Leptobolus insignis *decreases steadily with time; this brachiopod shows no significant geographic variation. Proportions of the head in* Triarthrus becki *change steadily with time and also with depth-related environmental conditions, as measured by ordination score (see Figure 3). The number of abdominal segments in* Flexicalymene senaria *changes with time only within an episode nearly one million years long. Depth-related clinal variation is most pronounced during this episode, as ordination-score contours indicate.* Leptobolus *and* Triarthrus *seem to show gradual evolution, and–depending on the time scale on which one views evolutionary change–*Flexicalymene *seems to show some combination of gradual and punctuated evolution.*

The important difference between these evolutionary histories and the schematic ones in Figure 1 is the hitherto unexpected importance of environment-related geographic variation in long-term evolutionary change.

"...evolution conforms to no one pattern."

CONCLUSIONS FROM THESE CASE HISTORIES

A general conclusion is that evolution conforms to no one pattern. Furthermore, the classification of observed patterns as gradual or punctuated may be partially subjective. For instance, reviewers of one of our recent grant proposals were about evenly divided in their interpretations of the evolutionary episode in *Flexicalymene*. Some saw gradual change over the course of the episode, and others saw the whole episode as a punctuation. (The proposal was funded anyway.)

A particularly interesting result of our work is the indication of frequent long-term involvement of geographic variation in evolutionary change. This may imply that microevolutionary adaptation to localized environmental conditions is important in determining long-term trends, and that macroevolutionary change can take place through microevolutionary processes, as in parapatric speciation.

Whatever its pace, evolution would seem to have important and hitherto little-known ecological dimensions that are just waiting to be explored through more exacting analysis of the fossil record.

John L. Cisne, a specialist in sedimentary geology and paleobiology, is an associate professor in the Division of Biological Sciences as well as in the Department of Geological Sciences.

In 1969 he received the B.S. degree in geology and geophysics from Yale, and in 1973 he received the Ph.D. in geophysical sciences from the University of Chicago. He joined the Cornell faculty after completing his graduate studies.

In addition to the work described here, Cisne's research has concerned the internal anatomy of trilobites as studied from high-resolution stereoscopic radiographs of rare fossils; the use of fossils in paleobathymetric mapping and in studying sea-level change; and patterns of sedimentation as related to the behavior of the earth's lithosphere and mantle under sediment loading.

Cisne is a member of numerous geological and biological societies and a fellow of the American Association for the Advancement of Science.

REMOTE SENSING IN GEOLOGICAL SCIENCES

by John M. Bird

During the flights of the Mercury, Gemini, and Skylab spacecraft, remarkable photographs of large regions of the earth were obtained; some aspects of the earth's atmosphere and surface have been seen only in these remote views. But valuable as it is for agricultural, meteorological, and geologic studies, aerial photography is now being augmented, and in some ways supplanted, by a technology that produces images obtained with electronic devices rather than photographic cameras. This technology, together with aerial photography, is generally known as remote sensing.

The development of electronic imaging sensors in the 1960s and 1970s has led to a multitude of electronic imaging devices that are now used on aircraft and spacecraft. Basically, these electronic imaging devices measure electromagnetic radiation and produce electrical signals that are subsequently processed to produce an image of the object being viewed. The sensors measure radiation in a much broader range of the electromagnetic spectrum than is recorded by photographic techniques. Early sensors were designed to measure emitted thermal radiation; now sensors are also used to detect ultraviolet, visible, near-infrared, and microwave (radar) radiation. Many of these sensors have the important capability of sampling narrower wavelength intervals with greater dynamic range than is possible with photographic film.

The electrical signal obtained from spacecraft sensors is converted to digital form and transmitted to Earth, where the data are recorded on magnetic tape. The digital data are then processed by various electronic and computing techniques. Interactive display devices are used to produce the images and to manipulate them so as to display features of interest. Many kinds of images can be produced. Some look like color photographs, although the only photographic technique involved is taking a picture of an electronic display device. The satellite "picture" now routinely shown on TV weather reports is produced in this way. An example of this type of image is shown on the inside back cover.

IMAGES TAKEN FROM SATELLITES AND AIRCRAFT

The best images for geologic studies have been provided by the LANDSAT satellites. The first of these, Earth Resources Satellite 1, was launched in 1972, and the fifth-generation satellite was launched in the spring of 1984. These five satellites have multispectral scanners that detect radiation from the earth in four wavelength intervals or bands. The amount of reflected solar illumination is measured in the green and red portions of the visible light spectrum, and in two near-infrared wavelength intervals. The satellites have repeating, systematic orbits that provide imagery of most of the earth's surface with a resolution of 80 meters. Although the multispectral scanners were designed for monitoring crops and other vegetation, the images have also greatly aided geologists. The repeating coverage makes it possible to monitor active geologic processes such as volcanic eruptions and glacier movement, and the image quality is such that maps can be made of different rock types and

"The near-global extent of coverage provides a way of studying the geology of inaccessible areas..."

structures. The near-global extent of coverage provides a way of studying the geology of inaccessible areas such as the Tibetan Plateau or the high Andes.

Because of the success of the initial multispectral scanners, additional, more advanced sensors are being deployed. The fourth and fifth LANDSATs, for example, are equipped with a thematic mapper, a type of multispectral scanner that has a resolution of 30 meters and measures radiation in seven bands, or spectral channels; one of the channels was specifically chosen for distinguishing different kinds of rock. The French will soon launch a satellite carrying a scanner (SPOT)

Figure 1

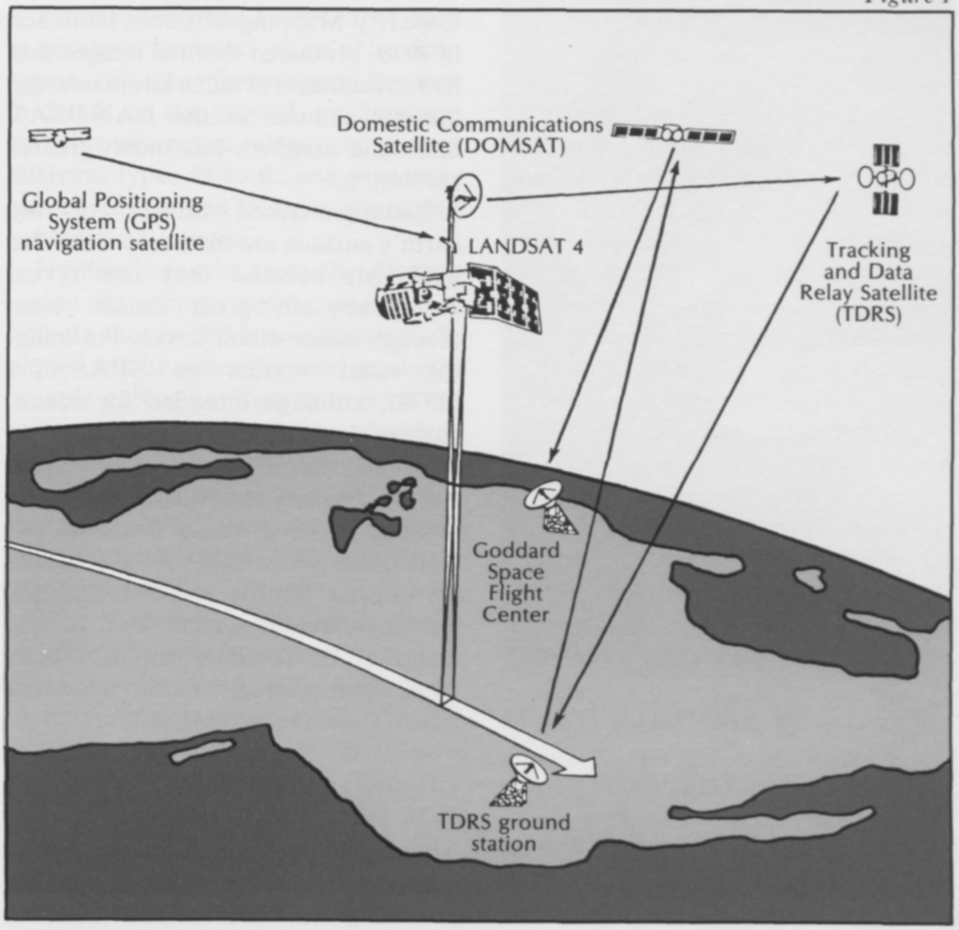


Figure 1. The LANDSAT system. The LANDSAT 4 spacecraft is characterized by its large mast, which supports an antenna for the tracking and data relay satellite, and by its single-wing solar array. Each sensing instrument uses a moving mirror assembly to scan in the crosstrack direction, and depends upon the relative motion of the spacecraft to achieve the along-track scan.

". . .image processing by computer of signals from electronic sensors has given us new and powerful 'eyes.'"

that will have 10-meter resolution and the capability of producing stereoscopic images. These images will greatly facilitate the study of geologic structures and landforms. Several very-high-resolution multispectral scanners, some with more than one hundred channels, have been designed for detailed observation of selected sites by aircraft.

Other sensors measure surface temperatures by sensing emitted thermal radiation, and these have been used to distinguish different rocks on the basis of their thermal properties. The Heat Capacity Mapping Mission, launched in 1978, produced thermal images that had a resolution of half a kilometer; the thermal channel of the LANDSAT thermatic mappers has much greater resolution.

Radar-generated images of the earth's surface are also very useful to geologists because they can reveal topography in great detail, even through dense cloud cover. An imaging radar system on SEASAT-1 (1978), although intended for ocean-surface surveillance, has assisted geologists in delineating topographically expressed structures. An experimental imaging radar designed for land observation (SIR-A) was flown on an early Shuttle Mission, and this fall an improved system (SIR-B) will be flown. These radar imaging systems distinguish geologic features on the basis of surface roughness.

CORNELL'S NEW FACILITY FOR REMOTE SENSING

These various kinds of images are increasing in quantity and quality and are providing valuable information for the geological sciences. Cornell researchers will be able to make good use of this resource. Snee Hall will have a dedicated image-processing facility—part of its large graphics laboratory—that is being provided with the help of funds from the National Science Foundation. We anticipate much activity in processing, synthesizing, and interpreting the great variety of images it is possible to produce from these data.

The image-processing device will be hosted by a VAX minicomputer that has been acquired by the Institute for Study of the Continents (INSTOC). Images will be displayed with a high-resolution color-monitor; users will be able to manipulate them interactively in a variety of ways, including zooming, scrolling, generating color composites, and adjusting colors. Standard image-processing functions such as those involving filtering, Fourier transforms, ratios, classifications, and geometric transformations will be performed very rapidly. It will be possible to register disparate data types to a common geometric projection, so that imagery from many different sensors can be compared directly. Data other than electromagnetic radiation measurements can also be registered and displayed, enabling users to integrate geophysical data sets such as gravity, magnetics, and topography, with remote-sensing images. The facility will be equipped to input data from magnetic tape, disks, a video-digitizing camera, and a large-format digitizing table. Hard-copy output will be in the form of photographs processed with a high-resolution recording camera system, or maps produced with a 2-

by-4-foot vector plotter equipped for eight-pen color work.

USING THE NEW RESOURCE FOR WORK IN GEOLOGY

The new facility will be used for a number of research programs underway in the department. Arthur Bloom, who is a principal investigator on the SIR-B mission, will be using radar images of the Andes region in Argentina to study modern geologic features, including active fault scarps, recent volcanic fields, river terraces, and glacial deposits. Terry Jordan and Rick Allmendinger are using LANDSAT images in a study of the active tectonics of the Andes, drawing comparisons to mountain-building processes that occurred in the western United States 100 million years ago. Allan Gibbs will be using remote-sensing data to complement his study of the geology and mineral-resource potential of the Amazon rain forest, an area where accessibility is especially poor. Bryan Isacks will be analyzing the location of earthquakes in seismically active zones of the earth. He will also be evaluating the uses of integrated geophysical data sets, working with gravity, magnetic, and topographic data from the Andes. An accompanying article by Bryan Isacks, in this issue, describes INSTOC's Andes project. The COCORP project, which uses seismic reflection profiles to reveal structures deep within the earth's crust, may use the system for interpretation of color displays. The facility will also be used to enhance optical and electron-microscopy images of minerals and fossils.

The use of remote-sensing data for geologic mapping is already under study at Cornell. David Harding, a National Science Foundation graduate fellow, and I are interpreting LANDSAT data pertaining to a geologically complex region in southwest Oregon that we have been studying for the past ten years. For this work, we have been using the image-processing facility in the School of Civil and Environmental Engineering, with the assistance of Warren Philipson and William Philpot. An objective of this project, which is supported by the National Science Foundation, is to develop criteria and techniques for using LANDSAT data to produce geologic maps of remote regions. Harding first mapped the area in detail, on the ground, to show the complex geometric relation of several different types of rock, and then proceeded to "remap" the region using LANDSAT images.

Harding's results from the Oregon region are very promising, and we anticipate that in the future, these techniques will be generally used to obtain reliable geologic information from remote regions more quickly and at less expense than is presently possible. The work of Harding and others shows that LANDSAT data will reveal new geologic information, seen only by remote sensing.

The remarkable developments in image processing by computer of signals from electronic sensors has given us new and powerful "eyes." In the geological sciences, we are just beginning to see with them.

John M. Bird, a professor of geological sciences at Cornell, has written several times for the Quarterly *on aspects of his research in geotectonics and orogeny, and collaborated with William A. Bassett and Maura S. Weathers on another article in this issue.*

FACULTY PUBLICATIONS

Current research activities at the Cornell University College of Engineering are represented by the following publications and conference papers that appeared or were presented during the four-month period March through June, 1984. (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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Cooke, J. R. 1984. Microcomputers in American higher education. Paper read at summer meeting, American Society of Agricultural Engineers, 24–27 June 1984, in Knoxville, TN.

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Furry, R. B., J. R. Hicks, M. C. Jorgensen, and *J. A. Bartsch.* 1984. Controlled atmosphere storage of celery. Paper read at summer meeting, American Society of Agricultural Engineers, 24–27 June 1984, in Knoxville, TN.

Gebremedhin, K. G., D. S. Durnford, and *R. A. Parsons.* 1984. A proposed wind load standard for agricultural buildings. Paper read at summer meeting, American Society of Agricultural Engineers, 24–27 June 1984, in Knoxville, TN.

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■ CHEMICAL ENGINEERING

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Mallo, P., and *C. Cohen.* 1984. Etude de l'hydrolyse dans les gels de polyacrylamide. Paper read at meeting of Société Chimique de France, 19–20 January 1984, in Strasbourg, France.

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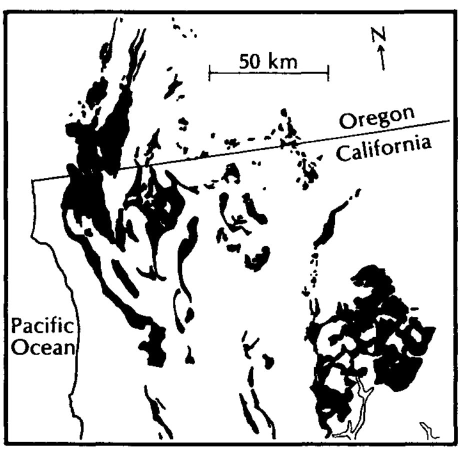
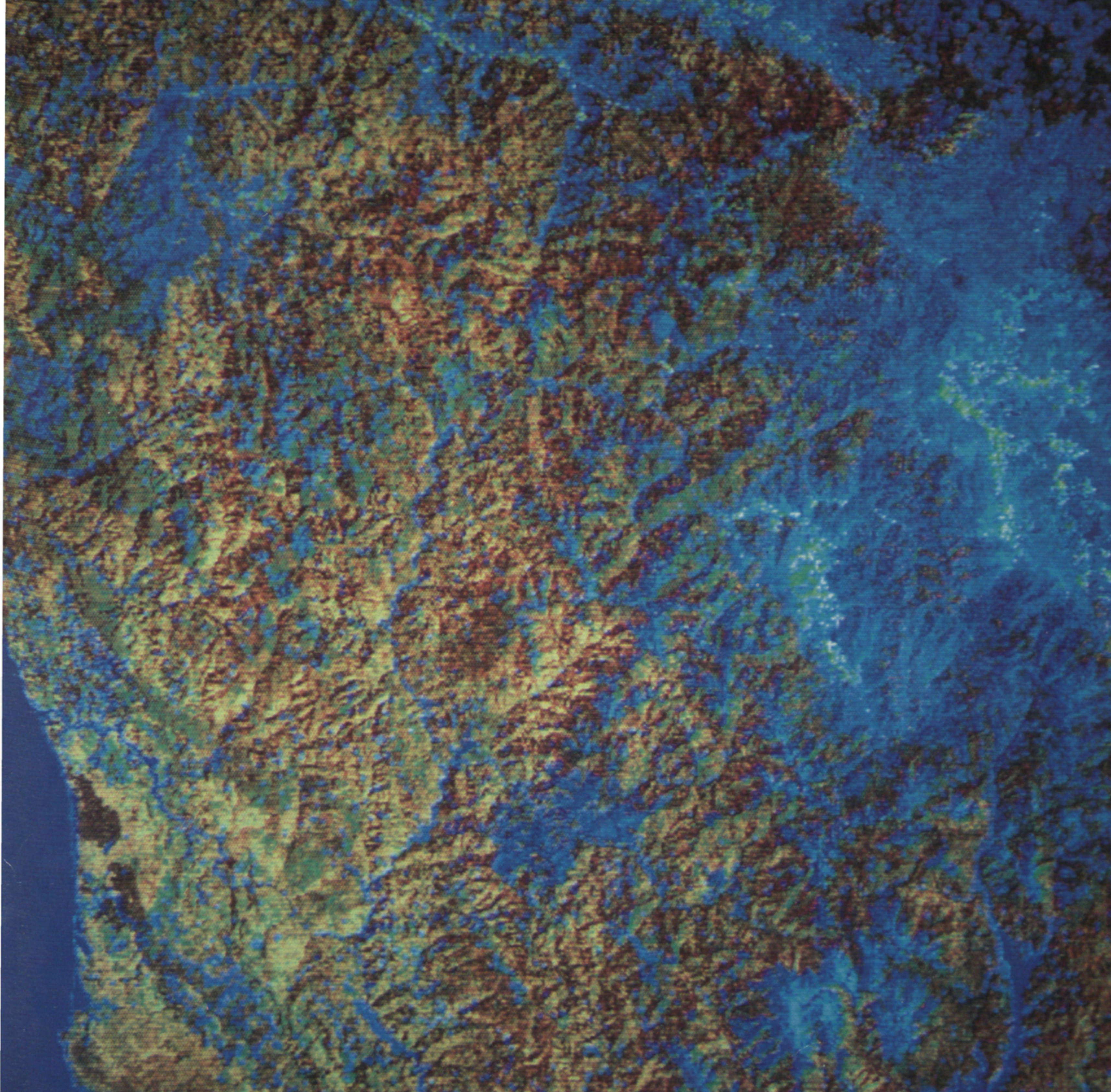


Opposite: A LANDSAT false-color composite image shows the Klamath Mountains of southwestern Oregon and northwestern California. The image is used for mapping the distribution of various rocks in the Klamath Mountains (see the article by John M. Bird). Heavily vegetated terrain appears orange and yellow; sparsely vegetated terrain appears blue and green; the dark blue area in the lower left corner is the Pacific Ocean; the light blue area in the upper right is the Shasta River Valley.

Left: This map shows the area in the LANDSAT image.



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