# A Special Issue on Geophysics & Planetary Science at Caltech

Engineering and Science

California Institute of Technology | October-November 1974

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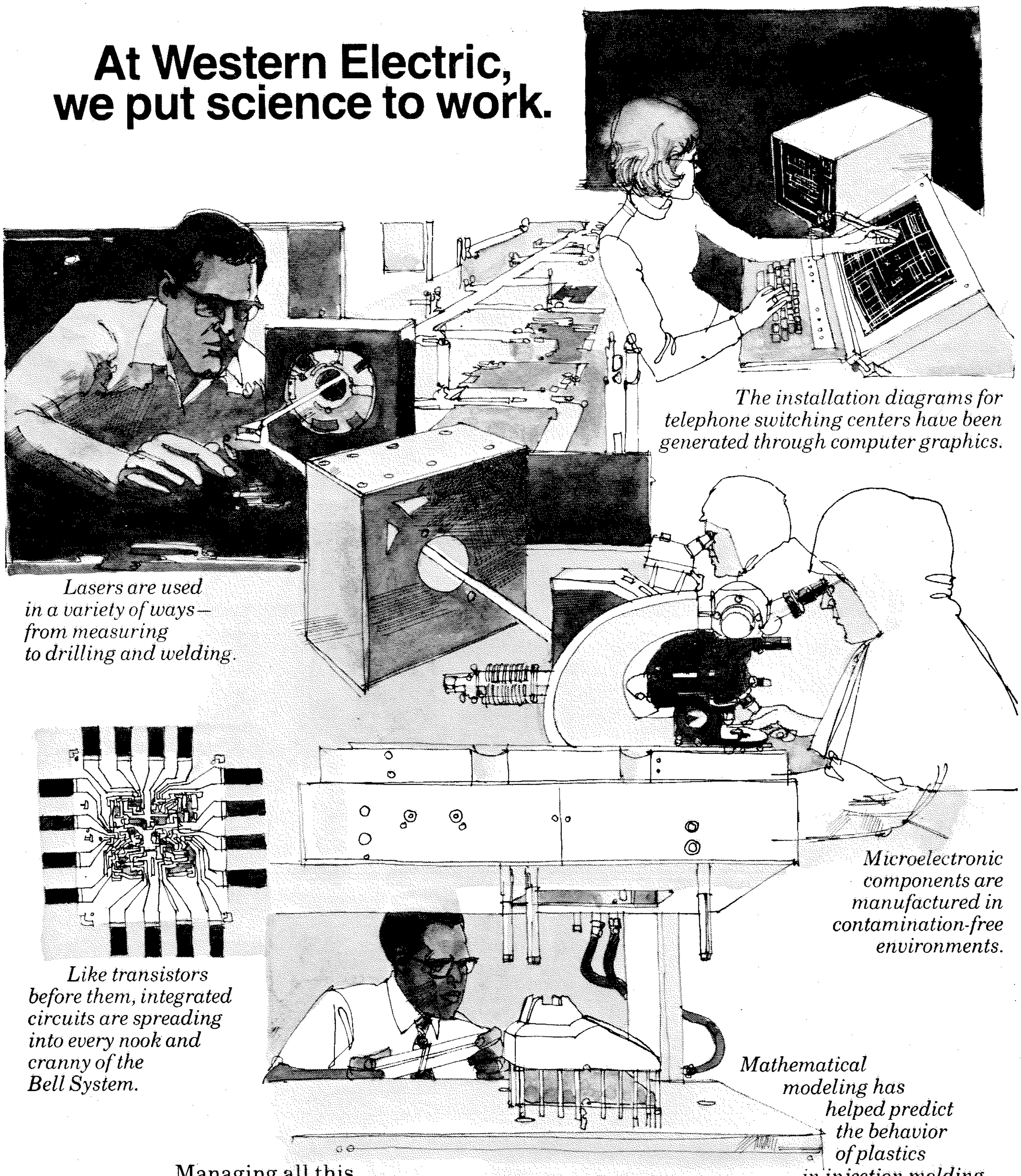

*The installation diagrams for telephone switching centers have been generated through computer graphics.*

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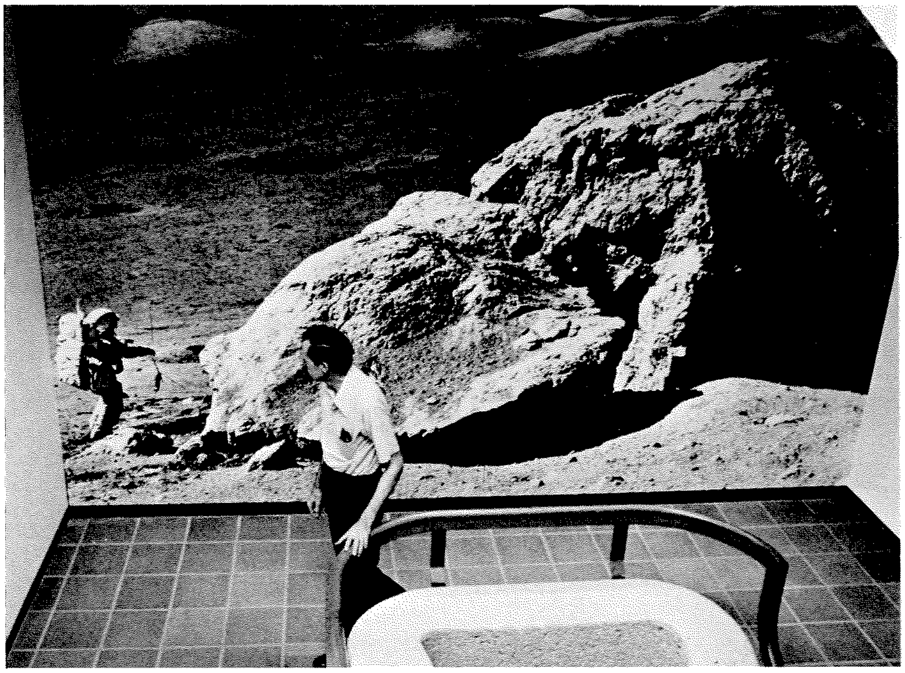
# Engineering and Science

October-November 1974/Volume XXXVIII/Number 1

## A Special Issue on Geophysics and Planetary Science

# In This Issue



**Walk by the Moon**

This gigantic photograph of Harrison Schmitt on the moon is one of the many spectacular features of Caltech's new Seeley G. Mudd Building of Geophysics and Planetary Science—as is the exterior detail shown below.

In this special issue, *E&S* takes the occasion of the dedication on October 31 of the new building to review some of the exciting research that will now be conducted there.

**The Contributors**

The contributors to this special issue are the researchers themselves—geophysicists and planetary scientists—who are now installed in the Seeley G. Mudd Building. We introduce them to you on pages 2, 3, and 43. And on page 45 we provide some quick notes for dullards, foot-draggers, and hopeless cases like the editorial staff of this magazine, who cannot seem to retain the basics of the metric system, along with certain other necessary technical matters.

STAFF: *Editor and Business Manager*—Edward Hutchings Jr.
*Managing Editor*—Jacquelyn Bonner
*Photographer*—Floyd Clark
*Design*—Doyald Young

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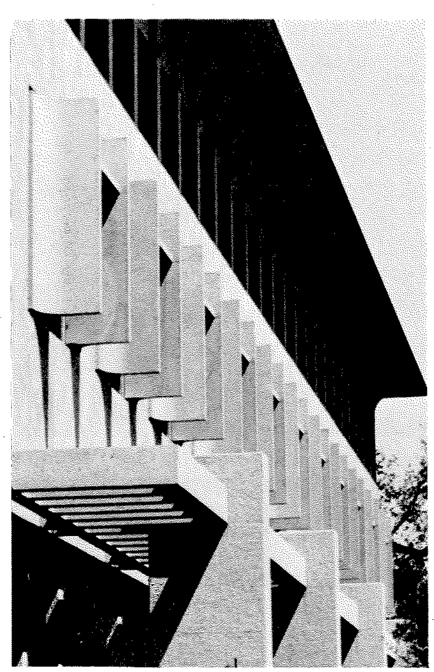


**Barclay Kamb**

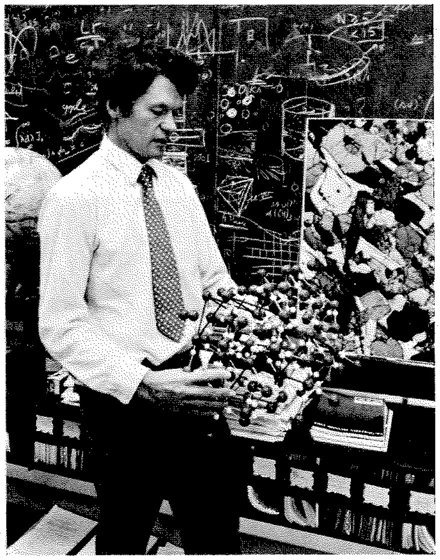
Caltech alumnus Barclay Kamb (BS '52, PhD '56) is professor of geology and geophysics and, since 1972, chairman of the Division of Geological and Planetary Sciences. For some years he has studied phenomena of rock deformation in the earth, particularly as exemplified by the flow of ice in glaciers. He has extensively studied the high-pressure forms of ice and their molecular structures, and has established relationships between forms of ice and certain silicate minerals. Kamb's research interests also include geologic structure, the atomic structure of crystals, and the nature of the recrystallization phenomenon in solids under stress. In "Geophysics and Planetary Science at Caltech" on page 4, Kamb introduces the division, the new Mudd building, and the contributors to this issue.

**Don L. Anderson**

Don Anderson, professor of geophysics, started his professional career in 1955, shortly after he graduated from RPI. His job was to look for oil in Montana, but that kind of prospecting lasted only a year. He spent the next two as a member of the U.S. Air Force doing research on ice—mostly in Greenland. Once out of the service, he began his graduate work at Caltech, receiving an MS in 1958 and a PhD in 1962. He was immediately appointed to the faculty, and he has been associated with the Seismological Laboratory ever since, becoming its director in 1967. Anderson is a distinguished scientist, and he is also a prolific contributor to scientific journals—his bibliography listing more than 120 titles. He turns his talents to historical review and a little prognostication, however, in "The Seismological Laboratory: Past and Future" on page 8.

**Clarence R. Allen**

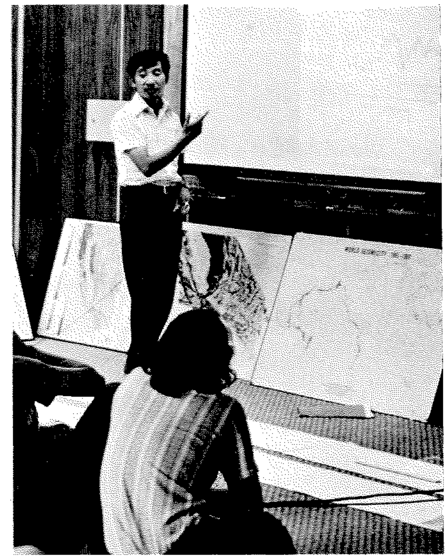
Ask a busy man when you want something done—like Clarence Allen, professor of geology and geophysics. He's on call all over the world to advise on faulting and seismicity, he carries a full research and teaching load, and he's an active campus citizen as well. Alumnus Allen (MS '51, PhD '54) served as interim director of the Seismological Laboratory in 1965-67, acting division chairman in 1967-68, and chairman of the faculty 1970-71. Currently he's a member of the Academic Freedom and Tenure Committee, and he was chairman of the faculty committee on the new geophysics and planetary sciences building. Needless to say, he generally turns up whenever and wherever there's an interesting earthquake. Fortunately for Allen, and the rest of us, there's air travel and air mail; the manuscript for "The Southern California Seismographic Network" (page 14) was mailed from Hong Kong.



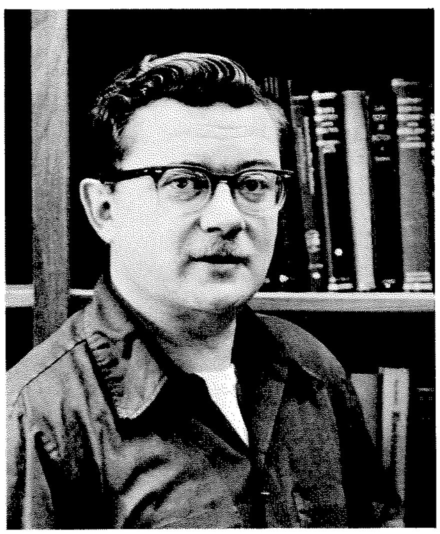
Kamb

**Hiroo Kanamori**

Hiroo Kanamori, a graduate of the University of Tokyo and for six years a member of the faculty of its Earthquake Research Institute, made his first trip to Caltech as a research fellow in 1965-66—at least partly as a result of having talked about the idea with Caltech's Hewitt Dix when Dix visited the University of Tokyo. During his year here, Kanamori developed methods for analyzing shock-wave data and worked on problems of anelasticity of the mantle and the structure of the core-mantle boundary. In 1972 he came back to the Institute as professor of geophysics. Kanamori's seismological interests range across a broad spectrum, but in "Earthquake Prediction" on page 18 he discusses one of the liveliest questions in geophysics today—whether, and how, earthquakes may signal their approach.



Kanamori

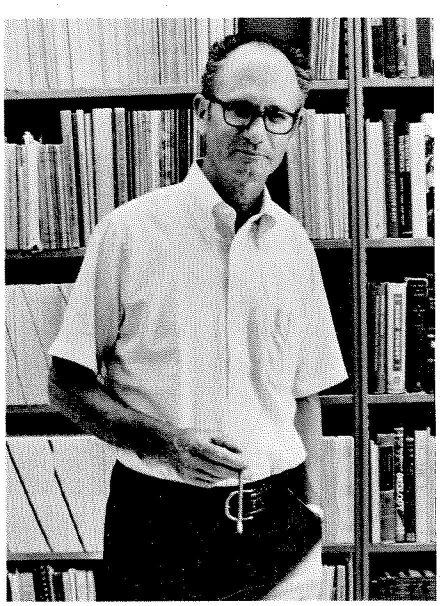


Anderson

**Thomas J. Ahrens**

"Laboratory equipment" is a phrase that refers to a multitude of interesting items, but it seldom includes a cannon. Nevertheless, that's what Thomas J. Ahrens wants—and has—all set into the concrete of the new Mudd building. In fact, he has several high-speed gas guns that he uses to launch projectiles at targets to create shock waves. What he is trying to do is to determine the effects of great compression on rocks and minerals. In "A Journey to the Center of the Earth—Solid State Geophysics at Caltech" on page 22, he describes his objectives. Ahrens, who earned an MS from Caltech in 1958, has been an associate professor of geophysics at the Institute since 1967.

Ahrens

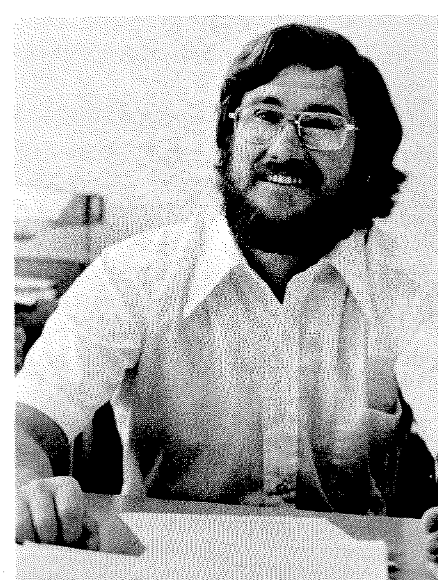


Allen

**Donald V. Helmberger**

Donald V. Helmberger, associate professor of geophysics, has been on the Caltech faculty since 1970. He graduated from the University of Minnesota and has an MS and PhD from UCSD. For two years he did postdoctoral work at MIT and then spent a year as assistant professor of geophysics at Princeton. A leader in a sophisticated theoretical approach to the interpretation of seismic waves, Helmberger analyzes seismograms from natural events and compares them with synthetic seismograms devised on a computer. These analyses provide geophysical information about the detailed nature of earthquake motions that has never before been obtained. In "Understanding Seismograms by Constructing Numerical Models" on page 26, he reports on his research.

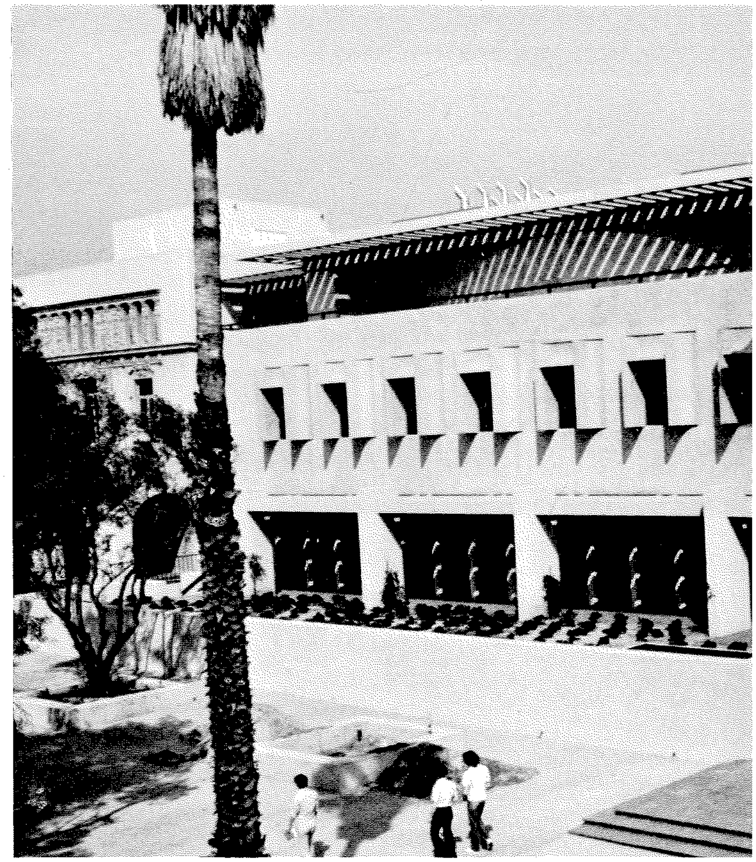
*continued on page 43*



Helmberger

# Geophysics and Planetary Science at Caltech

BARCLAY KAMB



The opening of the Seeley G. Mudd Building of Geophysics and Planetary Science is a notable milestone in the development of the Division of Geological and Planetary Sciences, and is an occasion calling special attention to the research and teaching in geophysics and planetary science at Caltech. This issue of *Engineering and Science* offers a collection of views of these activities, described by faculty members who are taking up their academic residence in the new building.

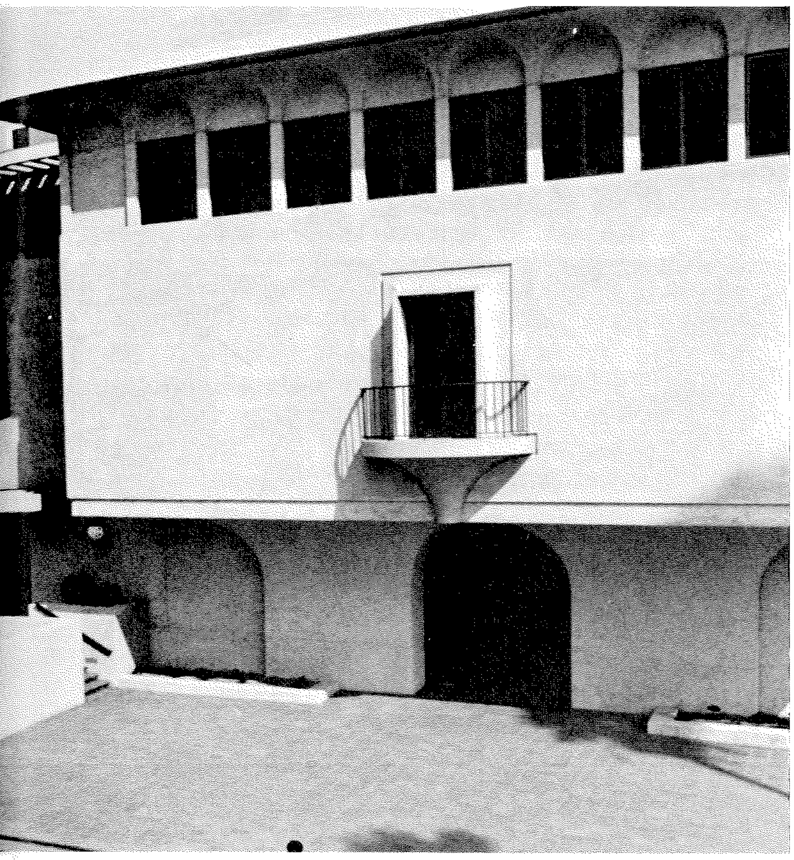
The disciplines of geophysics and planetary science have very different origins and histories at Caltech. In many ways their interests are opposite—geophysics looking inward to the earth's interior, planetary science outward to other worlds. And yet they also have much in common, and their mutual interests are certainly growing.

Geophysics as an academic discipline at Caltech dates from shortly after the inception of the Division of Geology and Paleontology in 1926. It began in earnest with the arrival in 1930 of Caltech's first professor of geophysics, Beno Gutenberg. The subsequent transfer of the Carnegie Institution's Seismological Research Laboratory to Caltech as part of the geology division, and the addition to the faculty of Charles Richter and Hugo Benioff, created a center of seismological research at Caltech that was soon renowned throughout the world.

Although formal courses in geophysics were taught on the campus, the research was conducted from the start at the Seismological Laboratory located in the hills to the west, where the seismographs could be placed on bedrock. This physical separation and a variety of other factors contributed to the development of rather independent traditions, styles, and loyalties among the groups in geophysics and geology. However, several field research projects were carried out jointly by John Buwalda and Beno Gutenberg and their students, notably geophysical explorations of the floor of Yosemite Valley, the Frazier Mountain thrust, and the Beartooth thrust in Wyoming.

The substantially expanded research program in geophysics that developed under the leadership of Frank Press in the fifties, and flowered in the augmented facilities of the Seismological Laboratory at the adjacent Donnelley Building, set the tone and style of seismology as we now know it at Caltech, and cultivated an attractive *esprit de corps* among faculty and graduate students that continues to this day. When at the same time the geology group on campus began to branch out into new research areas with strong emphasis on underlying physics and chemistry—geochemistry, for example—the possibilities for productive interchange between the geology and geophysics groups increased decidedly.

The physical separation continued, but Clarence Allen, whose early base was largely on the campus, pointed the way to closer ties by developing a close association with the Laboratory, and he eventually served two years as its acting director. The attractive research atmosphere and well-developed traditions of the Lab are enthusiastically maintained by its current director, Don Anderson, whose



"South Mudd"—
Caltech's new Seeley G. Mudd Building of Geophysics and Planetary Science flanks the existing Seeley W. Mudd Laboratory of the Geological Sciences—now known as "North Mudd."

broad interests have been instrumental in stimulating a number of new areas of research.

Planetary science is by contrast a very recent addition to the division, reflected in the change of the division's name to its current form in 1970. It grew out of the great scientific development that accompanied the space program. Especially because of its association with JPL, Caltech realized early in this development that it should help to provide the new studies of the solar system with solid academic foundations. The geology division foresaw in the impending growth of information about the planets an opportunity to gain greater insight into the earth, and it believed conversely that our understanding of the earth would be helpful in interpreting new data on the other planets. It therefore began to build a faculty that could pursue planetary science with these possibilities in mind, and that could thus interact fruitfully with the rest of the division.

We did not realize at first how far afield in science this would in fact lead us, or how greatly the scientific bandwidth of the division would be increased. Most of the new faculty members in planetary science have backgrounds, orientations, and interests quite divergent from those traditional in the division, and the boundary line has become somewhat shadowy here between our division and the Division of Physics, Mathematics and Astronomy, where several important kinds of planetary research are also carried out. Nevertheless, our new group in planetary science developed a good rapport with the rest of the division, functioning from the beginning as an integral part of it.

Perhaps this is due partly to the fact that much of the division plunged eagerly into lunar science as the Apollo program unfolded. The external features of the planets, observed from spacecraft, needed to be understood in terms of the internal structure of these bodies, and this opened an important area of common interest between planetary scientists and geophysicists, since ideas and techniques developed for studying the internal structure of the earth could be applied to the planets in general. Another example of common interests is the planned Viking 1975 landing mission to Mars, for which the geophysicists are providing a seismometer that will be able to give positive proof of the internal activity that was deduced by planetary scientists from observations of the planet's surface.

By the mid-sixties it was becoming apparent that research activities in geophysics were overflowing the available space in the Seismological Laboratory, and that development of planetary science was being hampered by insufficient facilities on the campus. At the same time, the disadvantages in the location of the Seismological Laboratory off campus were becoming more keenly felt. The idea of solving these problems and opening up new opportunities for geophysics and planetary science at Caltech by creating a new building on the campus germinated during Robert Sharp's chairmanship of the division and was successfully implemented under the chairmanship of Eugene Shoemaker. Achievement of the new building stems directly from the generosity of several donors. Initiation of the project was made possible by a large gift from the family of Dr. Seeley G. Mudd, long a friend of the Institute, and by a matching grant from the U.S. Department of Health, Education, and Welfare, because of the public-service contributions of the Seismological Laboratory in providing earthquake information.

The Mudd gift was the key to undertaking the project, and the building is named in honor of Dr. Mudd. It gives handsome testimony to the generosity that his family has shown to Caltech over the years, complementing prominently the existing Seeley W. Mudd Laboratory of the Geological Sciences, which has housed a good part of the division since 1938. These two beautiful buildings stand side by side facing Wilson Avenue on the west side of the campus and are connected at two levels. To distinguish them easily by name, we are informally calling the Seeley W. Mudd Laboratory "North Mudd" and the new Seeley G. Mudd Building "South Mudd."

As detailed planning for the new building revealed the many special features needed for the operations of the Seismological Laboratory and planetary science, it became apparent that the project was so extensive and complex that some of them could not be included without additional gifts. We were very fortunate in appealing to the generosity of several donors in support of these special needs: Mrs. Roland W. Lindhurst for the Laboratory of Experimental Geophysics, Mr. Ross McCollum for the Space Photography Library, Mr. Henry Salvatori for the divisional Seminar Room, and the Kresge Foundation for matching funds for these and other special laboratories.

To the donors, the Division of Geological and Planetary Sciences extends its very special thanks. They have made possible the beginning of a new era in the scientific life of the division and the Institute. To the Institute administration and to many of the division faculty who contributed to the project in numerous ways, to the architects who designed the building, and the contractor and workmen who built it—to all of these the division also owes a debt of gratitude. Our debt is especially great to Clarence Allen, who from the beginning and throughout the project carried the prime responsibility on behalf of the faculty for working out an attractive design to meet our numerous special requirements, and for watchfully following it through to completion. Many of the basic concepts in the building, and many novel and pleasing details, are due to his efforts.

What can we expect of geophysics and planetary science in the years to come? We can get an idea from the facilities provided in the new building.

For geophysics, which largely occupies the south wing, there is of course office space for faculty, students, and staff, and in addition an extensive complex of instrument rooms, work room, computers, seismogram library facilities, instrument and machine shops, and a special outfitting area for preparing seismic equipment for the field. The work in these facilities represents the heart of the Seismological Laboratory's operations in monitoring and interpreting earthquake activity in southern California and throughout the world, and in deciphering the internal structure of the earth from the propagation of seismic waves.

Other special laboratories such as the Helen and Roland W. Lindhurst Laboratory of Experimental Geophysics, laser Raman scattering laboratory, high-pressure laboratory, and X-ray laboratory represent new directions of research in geophysics aimed at understanding the properties of rocks and minerals at the high pressures and temperatures of the earth's interior.

The Gutenberg Library and Benioff Conference Room will provide the focal point for the frequent small, informal seminars and scientific "bull sessions," so stimulating to intellectual ferment and new ideas, that are one of the characteristic ingredients of the research atmosphere in the Seismological Laboratory.

For planetary science, which is mostly housed in the north wing, there are comparatively fewer special laboratories in the building because much of the work is theoretical or utilizes observational facilities away from the campus, such as optical and radio telescopes and spacecraft. Many of the observing instruments are developed here, however, so there are special optics and electronics laboratories.

The McCollum Library will house an extensive collection of spacecraft photographs of the planets, and will have special information-retrieval equipment for displaying the photographs and facilitating their selection and study. And a super-clean geochemical laboratory for studies of lead, uranium, and thorium in lunar samples testifies to the mutual interest of planetary scientists and geologists in studying the planetary bodies of the solar system.

For the division as a whole, the new building provides the Salvatori Seminar Room, which will be used as the gathering place for our division-wide seminars. Above all, the building creates a new proximity of geophysics, planetary science, and geology that will encourage increased interaction among them and will, we hope, lead to valuable new joint ventures in research and teaching.

A quick look at the interests of the faculty who are now located in the new building will give a good idea of what geophysics and planetary science at Caltech are all about, and where they are going.

In geophysics we have Professors Clarence Allen, Tom Ahrens, Don Anderson, Charles Archambeau, David Harkrider, Don Helmberger, and Hiroo Kanamori. Allen is an authority on faulting and seismicity throughout the world, and takes the lead in guiding the work of Caltech's network of seismograph stations in southern California. Much of the Lab's extensive work on the mechanism and seismic effects of the 1971 San Fernando earthquake was done under his leadership. He strives to relate the research in seismology to the practical concerns of earthquake engineering, and he is often called upon for expert advice by government agencies.

Ahrens studies the properties of rocks and minerals under ultrahigh-pressure shock waves, in order to understand the interior of the earth and planets. He also uses experimentally produced shock metamorphism as a tool for interpreting shock effects in lunar rocks.

Anderson's broad interests extend from classical seismology to the internal structure, thermal history, and origin of the planets. His theoretical interpretations in combination with Ahrens's experimental work promise to yield a definitive understanding of the phase structure deep within the earth's mantle.

Archambeau, Harkrider, and Helmberger analyze and interpret the propagation of seismic waves in the earth. Archambeau is particularly concerned with the generation of seismic waves by fault motions, with distinguishing between the seismic radiation from earthquakes and explosions, and with the use of finite-element analysis to study tectonic processes.

Harkrider concentrates on the analysis of surface-wave propagation and its coupling with air waves and tsunami waves. He is taking the lead in developing an on-line digital computing system for recognizing automatically the seismic signals from earthquakes the moment they are received at the Lab, and for determining earthquake locations immediately.

Helmberger's attention is focused on interpreting the earth's body waves by sophisticated computational methods that allow the complete wave-form of the seismogram to be generated synthetically and thereby used in deducing the earth's internal structure. He is also using these techniques to understand the strong ground motions that occur near the epicenter of an earthquake.

Kanamori's interests include many aspects of seismology, especially the earth's free oscillations and the structure of the crust and mantle, and also gravity, geothermal heat flow, and high-pressure physics. He is currently studying the possibilities of earthquake prediction, a vitally active field in which Clarence Allen, Don Anderson, and senior research fellow James Whitcomb are also participating. Many of the studies impinge on major questions of continental drift and lithospheric plate motion that are of central interest today in geophysics and, indeed, in the division as a whole.

The group in planetary science consists of Professors Peter Goldreich, Andrew Ingersoll, Duane Muhleman, Bruce Murray, and James Westphal. Goldreich studies the dynamics of planetary systems, particularly the way in which the rotational spins of the planets are coupled to their orbital motions around the sun, the changes in these motions with time, the gravity fields of planets, and the processes by which the planets could grow by accretion from an original solar nebula. He discovered the explanation of how radio emission from Jupiter is modulated by the planet's satellites. He also studies far-flung astrophysical problems such as neutron stars, pulsars (to which he applied earthquake concepts), and interstellar masers.

Ingersoll's primary interest is the dynamics of planetary atmospheres—for example, the motions associated with Jupiter's cloud bands and red spot, and the existence of instabilities in atmospheric motions. He analyzed the "runaway greenhouse" effect in Venus's atmosphere, and he has been active in a scientific controversy over the effect of disturbances in the sun's atmosphere on measurements of the sun's shape (oblateness), which has important implications as a test of the general theory of relativity. He has participated effectively in teaching freshman physics and a joint geology-engineering course in atmospheric science.

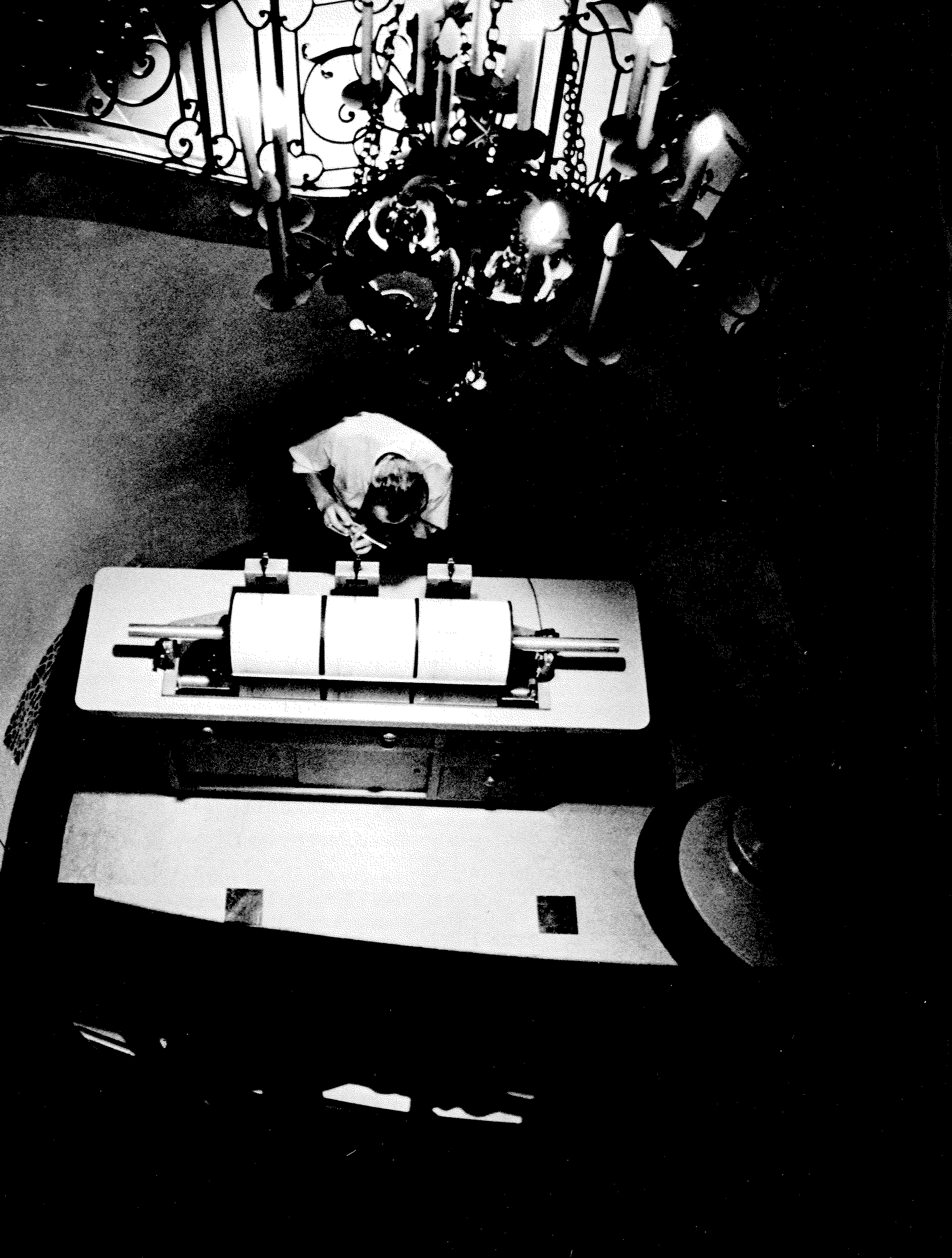
Muhleman uses the radio telescopes of Caltech's Owens Valley Radio Observatory to measure radio and microwave emission from the planets, which can be used to infer temperatures at or beneath the planet's surface or in its atmosphere, to estimate the planet's magnetic field, to detect lightning discharges or similar electrical effects (as on Jupiter), and to deduce planetary atmospheric pressures and compositions.

Murray's focus is the use of spacecraft photographs for exploration and interpretation of planetary surfaces. He is playing a leading role in learning about Mars, Venus, and Mercury from the photographs obtained in the Mariner missions.

Westphal is using new techniques of ground-based telescopic observation in infrared and visible light to increase our knowledge of planetary surfaces and atmospheres, and is also applying these powerful techniques to observing pulsars and distant clusters of galaxies.

A number of these topics are discussed by the faculty themselves in the following articles, which give by far the best idea of the flavor and vigor of geophysics and planetary science at Caltech.

What does it all add up to? In geophysics—a vigorous attack on the structure of the earth's interior and on the mechanisms of its internal activity, especially earthquakes. In planetary science—an endeavor to understand the variety of planetary structures and environments in a comprehensive way that will shed light on the evolution of the entire solar system and on the earth in particular. As we begin to pursue these broad and fascinating subjects in the new Seeley G. Mudd Building of Geophysics and Planetary Science, we can be sure, I think, that the research and teaching will more than ever live up to the motto "*labor bonus et multus*" that appears on the division's seal—good work and lots of it! □



# The Seismological Laboratory: Past and Future

DON L. ANDERSON

Moving into new and elaborate quarters is usually a matter of unqualified joy and anticipation. But anyone who has ever visited Caltech's Seismological Laboratory on North San Rafael Avenue will understand the mixed feelings with which the staff, students, and faculty recently left their home of 17 years.

With its long-time traditions, marble floors, paneled work areas, grand vistas, beautiful gardens, and private tennis court, working there had all the amenities of living in a mansion—including individual fireplaces and, at one time, private richly appointed bathrooms for each professor.

Slowly, however, the mansion was converted to more utilitarian scientific purposes. The sunporch and dressing room, originally attached to Hugo Benioff's office and complete with cedar closet and jewelry safe, were made into office space for Charles Archambeau and Hiroo Kanamori. The bathroom connected to Frank Press's office (formerly the master bedroom) was transformed into an office for a research fellow and a mathematician. Charles Richter's bathroom became a repository for reprints and journals, and Beno Gutenberg's bathroom became the ladies' room. A servants' bathroom became a student's office. At the end, of all the bathing facilities only the Director's shower remained, and many visitors were surprised to see a steady stream of tennis players in and out of his office around noontime.

Part of the inner patio was covered over to become the computer room. The kitchen was converted into a drafting room, and most of the larger closets became students' offices. The billiard room became a record-reading room. The walk-in silver safe in Clarence Allen's office was made into a storage vault for our ever expanding reprint collection. The garage became a high-pressure laboratory. Finally, we simply ran out of space. Even the hallways were full of seismic records and library overflow.

The environment, in fact, as well as the people, made the Seismological Laboratory a unique scientific facility—one to which many generations of geophysicists feel a great attachment. It provided an intellecually comfortable atmosphere that was conducive to productive thinking.

But its quarters and atmosphere were not the only unique aspects of what we now call—nostalgically already—the "Old Lab." In some respects it was a very high-class intellectual club. The students and faculty of the Seismological Laboratory have always formed a coherent group. The cohesion was partly an accident of history, the splendid setting of the Laboratory, and the common or intertwined research interests. Students have always been considered and treated as junior colleagues, differing from the faculty only in their experience and responsibilities. A strong *esprit de corps* exists, and there is some trepidation that this spirit cannot be transferred to our new surroundings. Our alumni in particular, who have gone off to more conventional environments, view the move as the end of an era rather than the beginning of one. I suspect they are all believers in Parkinson's laws.

Additionally, the staff and students of the Seismological Laboratory have always had a special responsibility to the public. Earthquakes (real or imagined), sonic booms, and announced or "felt" underground tests by the AEC generate floods of telephone calls from the press, the general public, and concerned public officials; and all of them must be dealt with promptly and diplomatically regardless of the press of other business.

In this sense we are a branch of the public relations office. This is a full-time responsibility since earthquakes occur during the night, weekends, and holidays, as well as in normal working hours. Even when things are quiet, records must be changed on the seismographs every day, and portable instruments must be ready to move on short notice. The financial and personnel ramifications of these responsibilities are obvious.

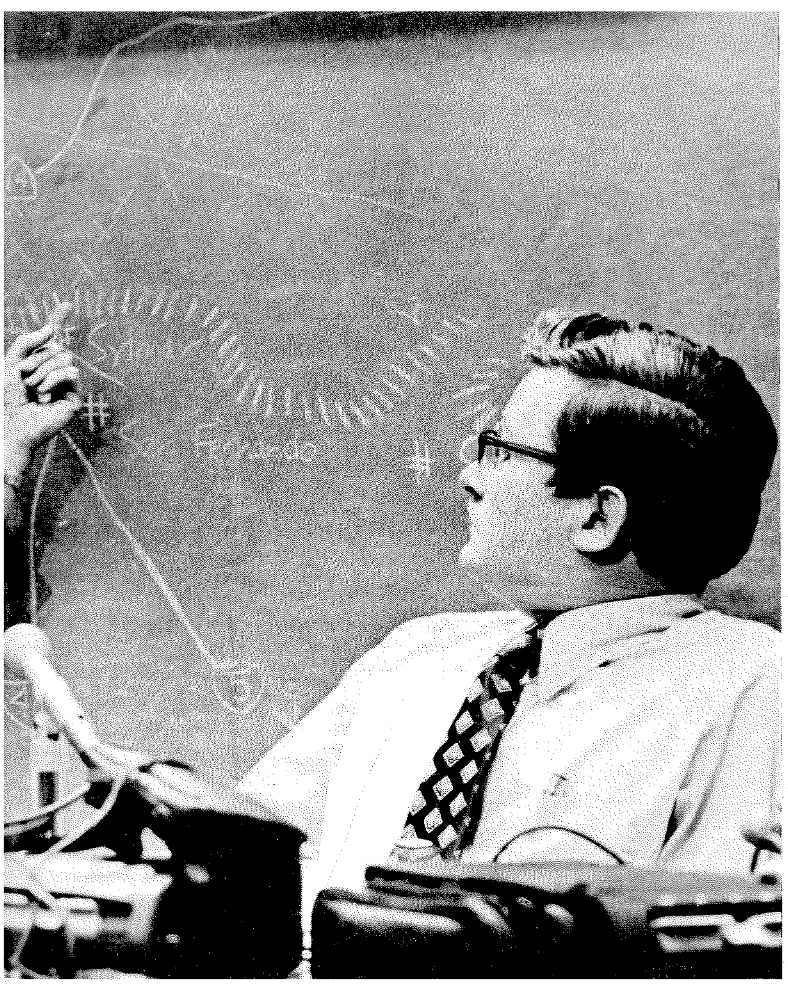
Even if we wanted to, we could not immerse ourselves completely in scholarly contemplation. This is "earthquake country," and the public wants, and needs, to know the information that exists only at our Lab—and this must be made available instantly. Students burning the pre-midnight oil are often the only immediate contact that a media representative has when he calls up to demand an interview for the 11 p.m. news regarding a 10:45 p.m. earthquake. Students mature quickly under this kind of pressure, and Caltech depends on them to give out accurate information and advice.

Since the Seismological Laboratory has been located off campus for so many years, many people are not aware of its activities or origins, except for what they read about in the newspapers or see on television. In fact, it is fair to say that local reporters and newscasters are more familiar with the environment at the old Laboratory than are most Caltech faculty. On the occasion of the dedication of the Seeley G. Mudd Building of Geophysics and Planetary Science, therefore, it seems appropriate to describe what the Seismological Laboratory is all about and where it is going.

The establishment and prospering of seismology and geophysics at Caltech are due in large measure to the vision and support of such men as George Ellery Hale, Robert Millikan, John P. Buwalda, Lee DuBridge, and Robert P. Sharp, all names well known to the Caltech community. (It is apparent that the importance of the study of earthquakes has been, and still is, recognized by astronomer, physicist, and geologist alike.)

One response to an earthquake is the invasion of the Seismological Laboratory by representatives of the media requesting information and reassurance from the experts, who in this case are . . .

The origins of the present Division of Geological and Planetary Sciences can be traced to Hale's desire to interest possible donors in giving money to build a Seismological Laboratory. He was motivated to secure funds for a central station for seismology in Pasadena by new instrumental developments which "seem to open up an entirely new field of research in geology, and may well be epoch-making in the development of that science." In his search for funds he concluded that "the only way in which an effective appeal can be made, however, is to plan a Department fully comparable in importance, both for advanced study and research, to the Departments of Physics and Chemistry; and donors would be especially attracted by the possibility of developing seismological research as a vital factor of the Department's study of the geology of Southern California."




These quotes are from a letter dated June 8, 1924, from Hale to John C. Merriam, president of the Carnegie Institution of Washington. Hale offered the cooperation of Millikan, and faculty members S. J. Barnett, A. A. Michelson, Paul Epstein, Harry Bateman, Richard Tolman, and A. A. Noyes, who could be called upon to conduct advanced courses and research in various branches of geophysics and the underlying mathematical problems. The division was established in 1926.

The Seismological Laboratory itself was founded in 1928 as a result of a 1921 study by the Carnegie Institution of Washington, a study based primarily on a 1916 report of H. O. Wood (at that time of the Hawaii Volcanic Observatory staff) on the desirability of establishing a network of seismic stations in southern California. Wood was placed in charge of the program and given the title of Research Associate, which he retained until his retirement. Wood's success in starting this program was helped considerably by the enthusiastic support of Hale, who was then director of the Mount Wilson Observatory. R. A. Millikan was a member of the Carnegie Advisory Committee and contributed to the establishment and maintenance of the headquarters at Pasadena.

In 1929 the Advisory Committee sponsored a conference at Caltech involving the ablest men working in seismology both in this country and in Europe. They were invited to evaluate the Carnegie program and chart the future course. The conference included Wood, Beno Gutenberg, Charles Richter, Hugo Benioff, Perry Byerly, James Macelwane, Sir Harold Jeffreys, and L. H. Adams. Shortly thereafter Gutenberg was brought to Caltech to work at the Seismological Laboratory, which was then still a Carnegie Institution endeavor with tenuous attachments to Caltech. Caltech provided the facilities, and Carnegie supplied all the funds and people.

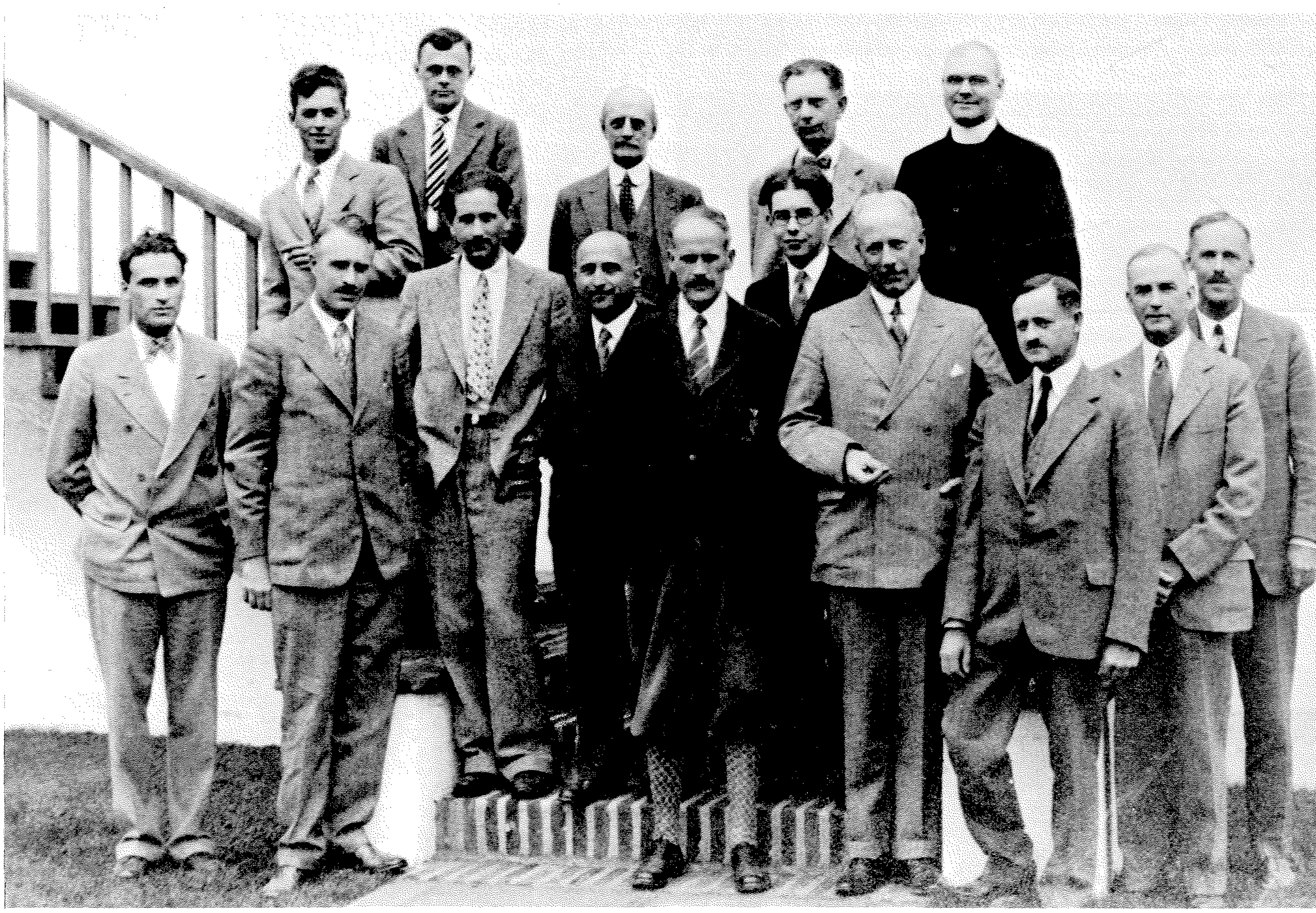
In the same year John Buwalda proposed to Millikan that half the staff of the Laboratory should be members of the Division of Geology (and Paleontology in those days). A new cooperative plan was worked out whereby the Lab

. . . Clarence Allen and Don Anderson. They are explaining what happened, and where, on February 9, 1971—and they're the first to credit everyone else at the Lab for turning out to help in the emergency.

was administered by a local joint committee of Caltech and Carnegie under the general direction of the Advisory Committee in Seismology. It was operated in this way by a committee of four from 1931 to 1937, at which time the administration was turned over to Caltech and Gutenberg was placed in charge. Carnegie decided to withdraw gradually from the operation and support of the Laboratory, but the general operation was still supervised by a committee in which Carnegie played a strong role.

In 1940 Millikan, Buwalda, and Vannevar Bush (then president of the Carnegie Institution) agreed that Gutenberg should be appointed executive officer of the Laboratory. He was named director in 1947 by Lee DuBridge, the new president of Caltech. Under Gutenberg's stewardship Pasadena became the world's center of seismological research.

By 1957 the staff had expanded from its original 4 to more than 20, and Robert Sharp, then chairman of the geology division, somehow managed to arrange purchase of an estate adjacent to the headquarters on San Rafael Avenue. This estate was complete with a 160-foot tunnel in bedrock in which to install seismic instrumentation, including Benioff's latest quartz strain meters. The two-laboratory setup—the original building renamed Kresge and the new one called Donnelley—continued to house the Seismological Laboratory until the recent move to campus.



These world authorities met at the Seismological Laboratory in 1929 to consider the status of seismology and to map worldwide research projects. Front row (left to right): Archie P. King; L. H. Adams; Hugo Benioff; Beno Gutenberg; Harold Jeffreys; Charles F. Richter; Arthur L. Day; Harry O. Wood; Ralph Arnold; John P. Buwalda. Top row: Alden C. Waite; Perry Byerly; Harry F. Reid; John A. Anderson; Father J. P. Macelwane.

Gutenberg retired as director in 1957, and Frank Press (now chairman of the Department of Earth and Planetary Sciences at MIT) was named the second official director of the Laboratory.

The publication record of the Laboratory really started in 1916 with H. O. Wood's two papers entitled "California Earthquakes—A Synthetic Study of Recorded Shocks" and "The Earthquake Problem in the Western United States." It was this latter paper that was to form the basis for the long-term plans which led eventually to the creation of the Seismological Laboratory and the network of seismic instruments. The Laboratory's techniques, procedures, instruments, and magnitude scales were adopted by the ever growing international community of seismologists. By 1940 the number of publications of the Laboratory had grown to 88; there were 170 by 1950; 370 by 1960; and 640 by 1970; and there are now in excess of 850. The published output has doubled approximately every ten years since 1935 and now includes contributions in lunar and planetary science, tectonics, behavior of materials at high pressure and temperature, and most other branches of geophysics.

Much of the present research at the Laboratory involves subdisciplines that did not even exist at the time of the move into the Donnelley Laboratory 17 years ago, or even in the transition period of the Gutenberg and Press eras. Some did not even exist at the time I became director in 1967. These subdisciplines include terrestrial spectroscopy, the study of the free oscillations of the earth after a great earthquake; strain and tilt seismology (long-term or permanent deformations of the earth); optical ultrasonics; solid state geophysics (the study of the properties of rocks and minerals at high temperature and pressure); lunar and planetary seismology; the science of synthetic seismology; plate tectonics; earthquake prediction (an old term but only recently a respectable science); dilatancy; earthquake physics (as opposed to earthquake mechanics or phenomenology); and inversion theory. Previous work such as development of wave propagation and dislocation theory, locations of earthquakes, and local and global tectonics, of course, continues.

Alumni of the Seismological Laboratory have dispersed across the country and around the world to start or strengthen geophysics departments in many universities. Recent graduates are on the professorial staffs of Harvard, Princeton, MIT, Columbia, Stanford, UC Berkeley, UCLA, UC Riverside, the University of Washington, Pennsylvania State, the University of Colorado, and the State University of New York.

All of these universities have outstanding programs in geophysics and, in fact, along with Caltech include the best departments or groups in the country. Other graduates have started programs in France, Chile, Turkey, and Israel. In recent years many of our graduates have gone into industry and to research labs in the U.S. government, most notably to the U.S. Geological Survey, which is in charge of the national program in earthquake prediction.

What does the future hold? Two articles in this issue explore the expansion of the Caltech Seismographic Network (the next step in monitoring southern California on the scale required for eventual earthquake prediction) and the anticipations of the new shock-wave facility. Other articles explain how more and more information about the earth and the earthquake source is being obtained from seismograms and the ultralong-period motion associated with faulting.

Space is too short to even itemize, much less detail, all the other research projects being undertaken by the staff and students of the Laboratory. However, some bear mentioning to complete the flavor and breadth of geophysics at Caltech. Recently several joint projects have been undertaken with JPL to apply space-age technology to tectonic problems. These include a program, using portable radio telescopes, to monitor deformations of the crust, and several laboratory and field projects to measure and understand changes in the physical properties of rocks just prior to failure. The seismometer that is to land on Mars in 1976 was designed at Caltech, and the seismic data it returns will be analyzed here. Much recent attention has been given to the origin, evolution, and internal structure of the moon and planets. We are trying to understand "deep mantle plumes," a recent concept that processes in the deep mantle ultimately control plate motions at the surface.

Breakthroughs cannot be anticipated, but the net result of the expanded and improved laboratory and field instrumentation, the continued evolution of new theories and techniques, and the continuous vigorous interaction of the transplanted geophysics group virtually assure that we will make even more rapid advances in understanding our earth and our neighbors in space than in the past. □

# The Southern California Seismographic Network

CLARENCE R. ALLEN

Virtually everything that is known about the seismicity of the southern California region comes from the seismographic network that is centered at Caltech's Seismological Laboratory. This network was initiated in 1926 by the Carnegie Institution of Washington, operated for many years by Caltech alone, and most recently expanded as a joint effort between Caltech and the U.S. Geological Survey. More than 17,000 local earthquakes have been located and analyzed by the Seismological Laboratory during this period, and it is this body of data, in addition to the sparse pre-1926 historic record of "felt" earthquakes, together with the geologic knowledge of our active faults, that primarily determines our judgments concerning earthquake risk in various parts of the southern California region.

In the years following the 1906 San Francisco earthquake, geologists came to realize that the San Andreas fault—the culprit responsible for the 1906 disaster—was just as much a feature to be feared in southern California as in the north. In fact, we now know that an earthquake comparable to the San Francisco event occurred along the fault's southern segment, adjacent to Los Angeles, as recently as 1857; and most geologists and seismologists expect a repeat of the 1857 event before San Francisco is again shaken by a great quake.

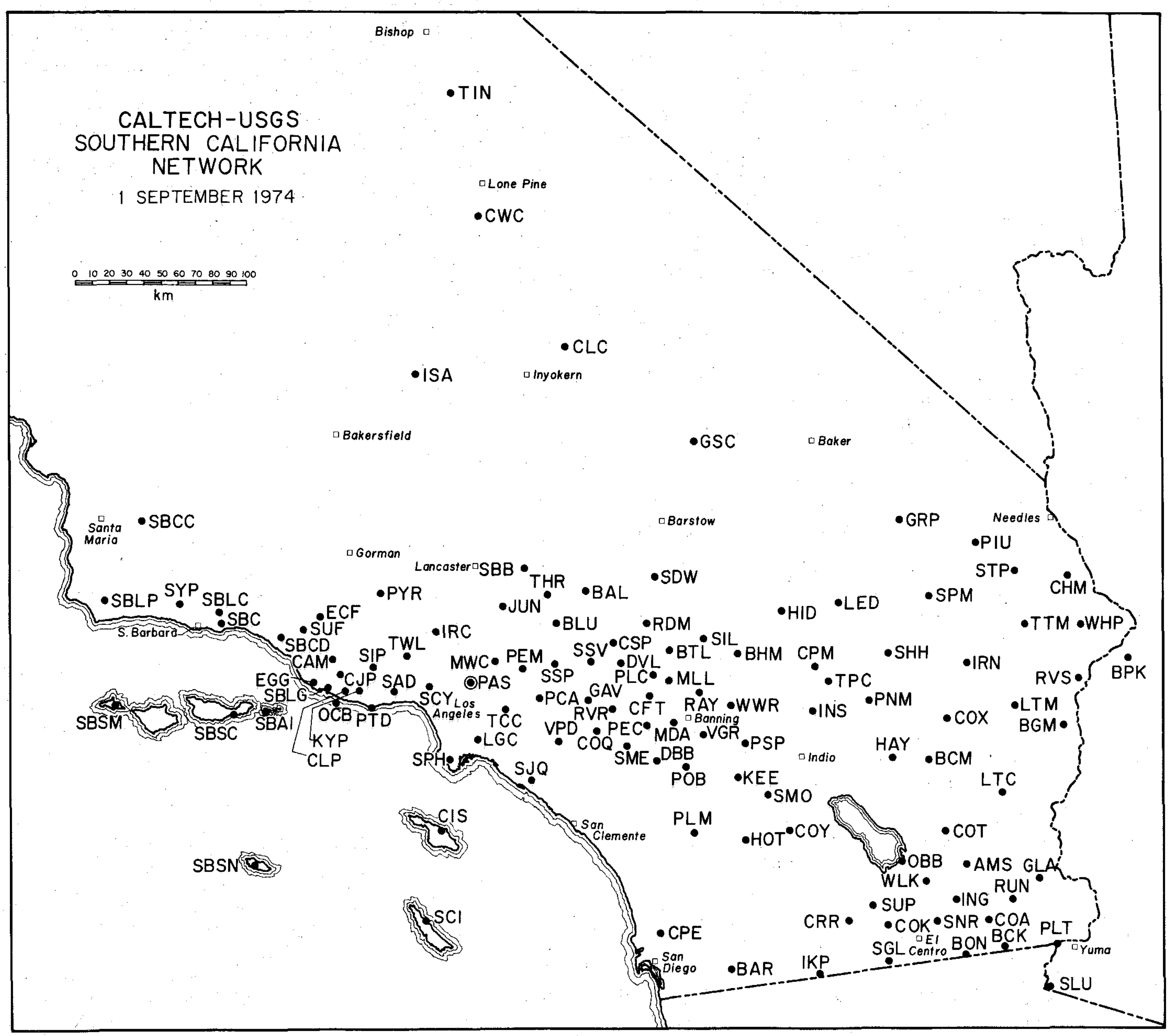
It is mainly because of this concern for southern California that pressures for a seismographic network began to be exerted as early as 1916, and by 1932, when routine epicentral locations of earthquakes throughout southern California began, some six outlying seismographic stations in addition to the Pasadena headquarters were in operation. And shortly thereafter, the team that was formed by Beno Gutenberg, Charles Richter, and Hugo Benioff had made Pasadena a byword among seismologists and geophysicists the world over.

Even with the recent move of the Seismological Laboratory to the new Seeley G. Mudd Building of Geophysics and Planetary Science on the Caltech campus, the Pasadena Seismological Station will have its instruments continuing to operate at the original location about three miles to the northwest. (They were located there initially because of the firm granitic foundation.) By 1974, however, the Pasadena station itself was only one of more than 100 stations comprising the southern California network—one of the largest and densest seismographic "arrays" anywhere in the world (right).

The original purpose of the Seismological Laboratory and its network was to help solve "the earthquake problem in southern California." Over the years, however, the work of the Laboratory has gradually encompassed broader geophysical problems. Even the seismographic network itself has been used as much in attacking wider problems, such as the nature of the earth's interior, as it has been in strictly local problems. Nevertheless, even after almost 50 years, "the earthquake problem in southern California" still remains a major challenge, and new impetus has recently been put into this effort, particularly with regard to earthquake prediction.

The one seismographic instrument common to all outlying stations, and in many cases the only instrument, is the so-called short-period vertical seismometer—recording the vertical component of ground shaking and "tuned" to those frequencies typical of local earthquakes (a few cycles per second). In addition, some stations contain instruments that record the horizontal component of ground motion, and one of the major contributions of the Laboratory has been the design and installation of long-period seismographs—instruments that are "tuned" to the low frequencies typical of distant earthquakes. And a number of key stations contain Wood-Anderson torsion seismographs—the instruments used in the original definition of earthquake magnitude by Richter in 1935, which are still essential in determining magnitudes of local shocks.

Seismographic stations of the southern California network, operated jointly by Caltech and the U. S. Geological Survey. Seismic signals from most of these stations are telemetered to Pasadena on leased telephone lines or by radio. A few such stations are operated cooperatively with other groups such as the California Department of Water Resources and the University of California at San Diego.




| | |
|---|---|
| **AMS** | Amos |
| **BAL** | Baldy Mesa |
| **BAR** | Barrett |
| **BCK** | Brock's Farm |
| **BCM** | Big Chuckwalla Mts |
| **BGM** | Big Maria Mts |
| **BHM** | Bighorn Mts |
| **BLU** | Blue Ridge |
| **BON** | Bonds Corner |
| **BPK** | Black Pk |
| **BTL** | Butler Pk |
| **CAM** | Camarillo Hills |
| **CFT** | Crafton Hills |
| **CHM** | Chemehuevi Mts |
| **CIS** | Catalina Island |
| **CJP** | Conejo Pk |
| **CLC** | China Lake |
| **CLP** | Clarks Pk |
| **COA** | Coachella |
| **COK** | Cook Rch |
| **COQ** | Corona Quarry |
| **COT** | Chocolate Mts |
| **COX** | Coxcomb Mts |
| **COY** | Coyote Mtn |
| **CPE** | Camp Elliot |
| **CPM** | Copper Mtn |
| **CRR** | Carrizo |
| **CSP** | Cedar Springs |
| **CWC** | Cottonwood |
| **DBB** | Double Butte |
| **DVL** | Devil Canyon |
| **ECF** | Echo Falls |
| **EGG** | Egg Rch |
| **GAV** | Glen Avon |
| **GLA** | Glamis |
| **GRP** | Granite Pass |
| **GSC** | Goldstone |
| **HAY** | Hayfield |
| **HID** | Hidalgo Mtn |
| **HOT** | Hot Springs Mtn |
| **IKP** | Inkopah |
| **ING** | Ingram Rch |
| **INS** | Inspiration |
| **IRC** | Iron Canyon |
| **IRN** | Iron Mts |
| **ISA** | Isabella |
| **JUN** | Juniper Hills |
| **KEE** | Keen Station |
| **KYP** | Key Point |
| **LED** | Lead Mtn |
| **LGC** | Lakewood Golf Course |
| **LTM** | Little Maria Mtns |
| **LTC** | Little Chuckwalla Mtns |
| **MDA** | Mt Davis |
| **MLL** | Mill Creek |
| **MWC** | Mt Wilson |
| **OBB** | Obsidian Butte |
| **OCB** | Ocean Bottom |
| **PAS** | Pasadena |
| **PCA** | Pomona |
| **PEC** | Perris |
| **PEM** | Pine Mtn |
| **PIU** | Piute Mts |
| **PLC** | Plunge Cr |
| **PLM** | Palomar |
| **PLT** | Pilot Knob |
| **PNM** | Pinto Mts |
| **POB** | Polly Butte |
| **PSP** | Palm Springs |
| **PTD** | Point Dume |
| **PYR** | Pyramid |
| **RAY** | Raywood Flat |
| **RDM** | Round Mtn |
| **RUN** | Ruthven |
| **RVR** | Riverside |
| **RVS** | Riverside Mts |
| **SAD** | Saddle Pk |
| **SBAI** | Anacapa Is |
| **SBB** | Saddleback Butte |
| **SBC** | Santa Barbara |
| **SBCC** | Colson Canyon |
| **SBCD** | Casitas Dam |
| **SBLC** | La Cumbre Pk |
| **SBLG** | Laguna Pk |
| **SBLP** | Lompoc |
| **SBSC** | Santa Cruz Is |
| **SBSM** | San Miguel Is |
| **SBSN** | San Nicolas Is |
| **SCI** | San Clemente Is |
| **SCY** | Stone Canyon Res |
| **SDW** | Sidewinder Mine |
| **SGL** | Signal Mtn |
| **SHH** | Sheephole Mts |
| **SIL** | Silver Pk |
| **SIP** | Simi Pk |
| **SJQ** | San Joaquin Res |
| **SLU** | San Luis |
| **SME** | Santa Rosa Mine |
| **SMO** | Santa Rosa Mtn |
| **SNR** | Schaffner Rch |
| **SPH** | San Pedro Hill |
| **SPM** | Ship Mts |
| **SSP** | Sunset Pk |
| **SSV** | San Sevaine |
| **STP** | Stepladder Mts |
| **SUF** | Sulfur Ridge |
| **SUP** | Superstition Mtn |
| **SYP** | Santa Ynez Pk |
| **TCC** | Turnbull Canyon |
| **THR** | Three Sisters |
| **TIN** | Tinemaha |
| **TPC** | Twentynine Palms |
| **TTM** | Turtle Mts |
| **TWL** | Twin Lakes |
| **VGR** | Vista Grande |
| **VPD** | Villa Park Dam |
| **WHP** | Whipple Mts |
| **WLK** | Wiest Lake |
| **WWR** | Whitewater |

The traditional and still widely used method of seismographic recording has been by means of a fine light spot focused on a sheet of photographic paper mounted on a rotating drum. The paper must of course be changed daily, and over the years a number of organizations have contributed to our understanding of local earthquakes by providing personnel to change records. For example, stations at Tinemaha (TIN) and Cottonwood (CWC) are serviced daily by personnel of the Los Angeles Department of Water and Power, China Lake (CLC) by the U.S. Navy, Hayfield (HAY) by the Metropolitan Water District, and Riverside (RVR) by the Riverside Fire Department. Because the timing of the arrival of earthquake waves at a station is critical—normally measured to the nearest tenth of a second—each station must be equipped with a radio receiver that is programmed periodically to receive U.S. Bureau of Standards time signals, so that the station chronometer (which puts a mark on the record every minute) can be calibrated against a standard time base.

Partly because of these logistical problems—the necessity for daily servicing and the maintenance of radio receivers at each station—almost all of the network expansion since 1966 has been with equipment that continuously telemeters signals to Pasadena, using a frequency-modulated tone on leased telephone lines or by radio links. In this way, the size of individual stations can be reduced to a simple buried box (right, above), and the time code can be added to all signals together at Pasadena. In addition—and perhaps most important—the signals are immediately visible in Pasadena, so that an earthquake can be located as rapidly as the data can be processed. One of our principal projects at the moment is to feed the telemetered signals directly into a computer on a real-time basis, so that an earthquake location and magnitude can be automatically obtained within a few seconds of the event. Preliminary results suggest that this should be possible within the near future, utilizing the Seismological Laboratory's new NOVA 1200 "mini" computer (right).

A Caltech telemetered seismometer vault, with an AT&T microwave repeater station in the background, at station GLAMIS, near the California-Arizona border north of Yuma.

Graduate student Larry Burdick locates an earthquake using the Laboratory's NOVA computer.

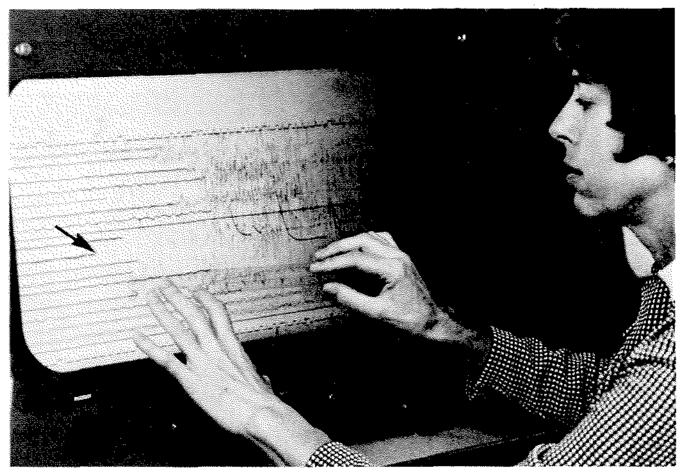
Even with the present system of data analysis at the Laboratory, in which the arrival times of seismic signals from the various stations are read manually and these data then entered directly into the computer keyboard, relatively quick epicentral locations are possible. The 1971 San Fernando earthquake, despite its 6:01 a.m. occurrence, was accurately pinpointed within about one-half hour. And the similar sized Borrego Mountain earthquake of 1968, which occurred at about 6:30 p.m., was located quickly enough so that portable instruments were operating in the epicentral area (a 200-mile drive from Pasadena) and the fault trace identified in the field by midnight.

One of the public service obligations of the Laboratory, in addition to serving the news media, is the notification of responsible authorities concerning potentially damaging earthquakes. For every local shock above magnitude 5.0, we must relay prompt epicentral and magnitude data—on a 24-hour basis—to federal and state disaster authorities and agencies such as the California Division of Safety of Dams and the U.S. Army Engineers.

During the past couple of years, a major expansion of the network has taken place in collaboration with the U.S. Geological Survey, which has not only provided additional funding but has also stationed two Geological Survey scientists at the Seismological Laboratory in connection with management of joint parts of the network. A total number of 300 stations is envisaged within the next few years, and it is clear that this network expansion will also necessitate improved data analysis facilities and methods.

Other groups besides the Geological Survey continue to support parts of the network operation. Particularly in recognition of the Laboratory's public service activities, the State of California is now providing limited annual support, and the Office of Naval Research has recently helped with the offshore stations and epicentral determinations. Likewise, the National Science Foundation and the Atomic Energy Commission have aided the network. And a particularly valuable source of help for many years has been the Earthquake Research Affiliates, a group of private companies and public utilities that give continuing support both to Caltech's Seismological Laboratory and to its earthquake engineering group.

What is the scientific justification for a 300-station network? The opportunity for greatly improved earthquake locations is probably not sufficient argument in itself, although this will certainly provide added insight into the nature and exact locations of our active faults, and more homogeneous statistics will be valuable for engineering purposes. But our real hope is that by continuously monitoring earthquakes and their physical parameters, we will recognize temporal changes that systematically precede earthquakes, and thus, eventually, develop an earthquake-prediction capability. Members of the Laboratory staff have already observed marked changes in seismic velocities that apparently preceded two local earthquakes in a way that is consistent with theoretical models of strain build-up and resulting fracture. But to test the general applicability of this model, far greater seismographic coverage is necessary than we have at present.



Technician Shirley Fisher reads a record of the San Fernando aftershock of March 9, 1974 (magnitude 4.5). Telemetered seismic signals from 18 outlying stations are recorded together on 16-mm film (here enlarged), with WWVB radio time signals at top and bottom. The first arriving signal (arrow) is from Iron Canyon, the station closest to the epicenter. More distant stations have successively later arrivals.

Perhaps the day is not too far off when the Seismological Laboratory will not only be reporting earthquakes *after* they happen, but we will have also developed a predictive system that is sufficiently reliable for some sort of meaningful warnings to be issued *before* an event. This field involves many very serious problems, both scientific and social, but it is also probably the most exciting research effort in which the southern California network has ever been involved. □

# Earthquake Prediction

HIROO KANAMORI

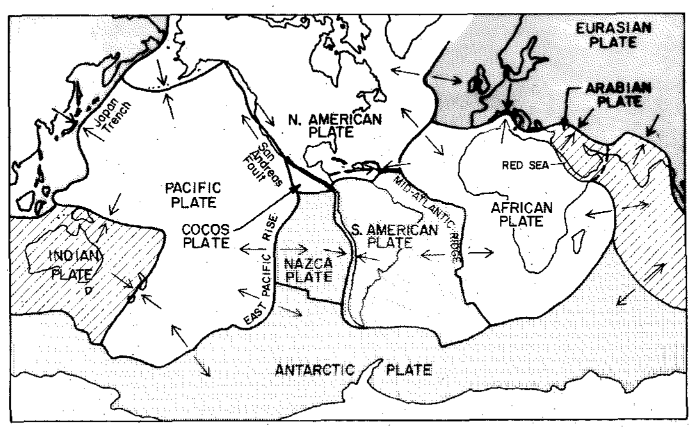
**By nature, earthquake prediction is only possible with some statistical uncertainty. Methods are being developed to make this uncertainty small enough for practical purposes**

The earth's surface consists of about a dozen large blocks, called plates, which are moving relative to each other. Although the cause of their movement is not fully understood, the evidence for such movement is firm. The relative motion between the plates causes strains and stresses in the earth's crust near the plate boundaries. When the stress exceeds the strength of the crustal rocks, fractures occur and elastic waves (seismic waves) are generated. An earthquake refers to either this fracture phenomenon itself, shakings caused by the elastic waves, or both.

It is probably no use repeating here how disastrous earthquakes can be—and they may be even worse in years to come, when we will have greater population concentration in urban areas, more structures, nuclear plants, reservoirs, water and gas pipe lines, and so on. Prediction, and possibly control, of earthquakes is naturally becoming an increasingly important subject on which major research efforts have been concentrated in recent years. However, an earthquake, as a fracture phenomenon, is a stochastic process, a process which is controlled by a number of accidental factors, and prediction of such stochastic processes is an exceedingly difficult task.

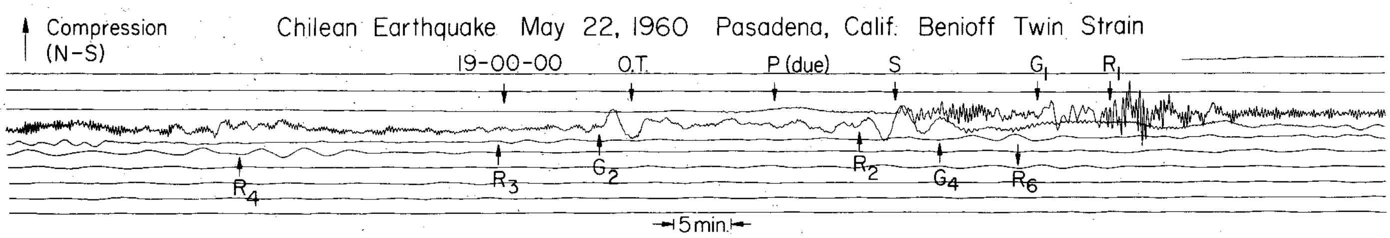
Suppose we squeeze a piece of rock. It eventually fractures, but not at a definite point. Sometimes it breaks at $5 \times 10^{-5}$ strain (relative deformation), but sometimes it can withstand up to $5 \times 10^{-4}$ strain. The breaking point is greatly affected by the configuration of a number of small cracks in the rock, and the behavior of the individual cracks is too complex to analyze. Thus, even if we know, by some means, that the strain in the earth's crust is about $10^{-4}$, we can only say that the probability is high that an earthquake will occur, but it is not possible to tell precisely when. The question is how to reduce this uncertainty so that a useful prediction can be made.

At first this seems almost hopeless if we consider the rate of the plate motion, which is typically 10 cm/yr. This slow rate can cause a strain rate of only $10^{-6}$/year or so. Since




The principal tectonic plates constituting the earth's surface. Major earthquakes occur along the boundaries of the plates. The pointed arrows indicate the direction of the relative motion of each plate, in that particular area of its boundary.

Seismogram of the great Chilean earthquake of 1960, recorded in Pasadena. $R_2$, $R_4$, and $R_6$ are long-period waves circling successively around the earth. These waves make up the earth's free oscillations, and convey information regarding the long-period characteristics of the earthquake source.



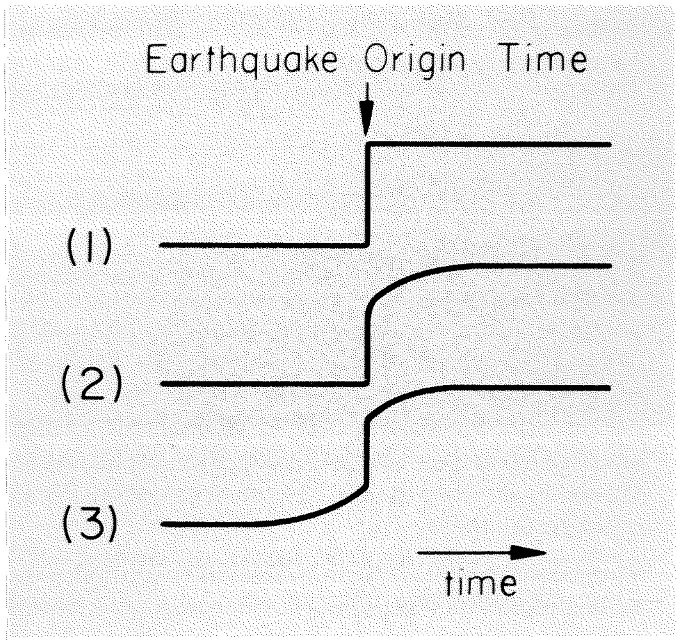

the breaking strain of the crustal rocks fluctuates approximately from $5 \times 10^{-5}$ to $5 \times 10^{-4}$, this slow strain rate means a fluctuation of occurrence time of earthquakes from $(5 \times 10^{-5}/10^{-6}) = 50$ years to $(5 \times 10^{-4}/10^{-6}) = 500$ years. Obviously, this fluctuation is too large to be useful for practical earthquake prediction. How, then, can we make earthquake prediction a reality? During the past decade earthquake research has made significant progress in understanding the physics of earthquakes, thereby opening the way to the establishment of a physical basis of earthquake prediction.

An earthquake is a physical phenomenon extending over a very wide time scale, typically from 0.1 second to hours, and even to an infinitely long time. In order to fully understand earthquakes, it is absolutely necessary to study earthquakes over this wide period (frequency) range. Earthquake effects are most obvious at periods of 0.1 to 1 second because it is in this range that earthquakes are felt by people and buildings and various structures are shaken. It is, therefore, natural that the first attempt to measure the "size" of earthquakes was made in this period range. In 1935, Charles F. Richter, working with Beno Gutenberg, first director of Caltech's Seismological Laboratory, initiated an earthquake magnitude scale which later became known as the Richter Scale. Despite its very simple definition, it proved to be a surprisingly useful parameter for quantizing relatively short-period earthquake phenomena.

Gutenberg and Richter further developed this magnitude scale and applied it to all types of earthquakes in the world. This work, later crystallized in the monumental study *The Seismicity of the Earth,* truly forms the basis of seismology today.

On the other hand, development of very-long-period instruments, particularly by Hugo Benioff, Frank Press, and Caltech's technical staff, opened up a new vista in seismology which culminated in the detection of the earth's free oscillations following the great Chilean earthquake of 1960. It had been known theoretically that the earth, as an elastic sphere, may vibrate with a fundamental period of about one hour if excited by an earthquake. Much to the excitement of the world's geophysicists, this one-hour-period oscillation was detected, for the first time, by those sensitive instruments; the amplitude of this oscillation at the earth's surface was only $10^{-1}$ cm or so—about $2 \times 10^{-10}$ of the earth's radius.

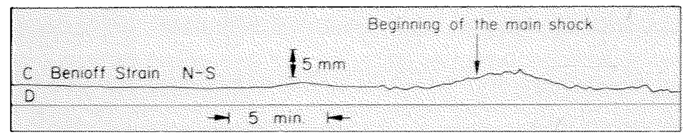
These developments in instrumentation, from short-period to long-period, as well as in various theories and analysis techniques, eventually led us to understand what is happening at the origin of an earthquake. Now it has become widely accepted that, to a good approximation, the source of an earthquake is a sudden slip (elastic rebound) across a more or less planar surface, called a fault plane. The product of the slip, $D_0$, and the area of the fault plane, S, gives a good measure of the size of earthquakes at long periods. For example, the San Fernando earthquake of 1971 had $D_0 \approx 2$m and $S \approx 10 \times 10$ km$^2$; i.e., $D_0S \approx 2 \times 10^{14}$ cm$^3$. In contrast, the great Chilean earthquake of 1960 had $D_0 \approx 30$ m and $S \approx 800 \times 200$ km$^2$, or $D_0S = 5 \times 10^{18}$ cm$^3$. In other words, it would take as many as 25,000 San Fernando earthquakes to make up a single Chilean earthquake. Thus, as far as physical size is concerned, the San Fernando earthquake is almost negligible as compared with the gigantic Chilean earthquake; yet the two earthquakes have equally strong social impact, and therefore are equally important from the point of view of earthquake prediction. However, prediction of smaller events would be more difficult, because their geophysical effects are less pronounced.




Different types of earthquake slip—(1) simple elastic rebound, (2) elastic rebound with postseismic slip, (3) elastic rebound with preseismic and postseismic slips.

There is no question that the seismic slip takes place more or less abruptly, as schematically shown above. However, its details are still unknown. For several earthquakes, there is fairly good evidence that the more or less jerky seismic slip was followed by a relatively slow slip, usually called creep or aseismic slip. These aseismic slips indicate that the rocks near the fault exhibit significant anelasticity; they deform gradually even after the tectonic stress is relieved by the earthquake faulting.

If they behave anelastically after the earthquake, why not before the earthquake? Although such a preseismic slip seems quite reasonable, no convincing evidence has been found. One piece of evidence, however, was found for the Chilean earthquake of 1960. In that year Benioff was experimenting with special long-period strain seismographs at Pasadena, and one of his instruments recorded very unusual long-period waves which arrived at Pasadena before the onset of the catastrophic main shock. Since Pasadena is about 10,000 km away from Chile, this observation suggests that a large-scale deformation (in terms of $D_0S$, $D_0S \approx 5 \times 10^{18}$ cm$^3$) had taken place before the main shock. Although this was indeed a remarkable observation, the excitement brought about by the detection of the free oscillations was so great that the precursor waves apparently remained unnoticed or forgotten for a long time. It was only recently that these long-period waves were interpreted properly in terms of a preseismic slip.




The very beginning of the ground displacement caused by the great Chilean earthquake of 1960, recorded at Pasadena. The arrow shows the onset time of the catastrophic main shock. A gradual motion begins before that time.

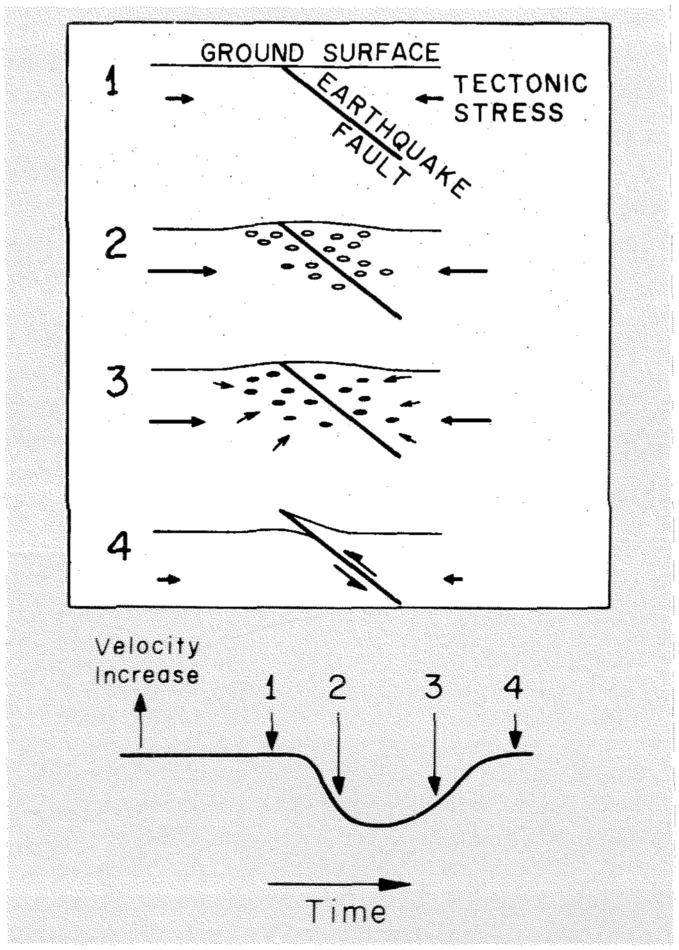
If this preseismic slip is real, and if it is characteristic of at least certain types of earthquakes, it will provide an important clue to earthquake prediction. Such preseismic slips indicate that the crustal rocks exhibit anelastic, and nonlinear, behavior before a major fracture. This anelastic deformation is eventually accelerated into the more catastrophic failure of the main shock. The details of this process and how long before the main shock it begins are not known. It may begin minutes, hours, days, or even years before the event. However, if such an accelerated process does take place before the earthquake, the range of the uncertainty in the occurrence time can be significantly narrowed by detecting the commencement, and monitoring the development, of the accelerated process.

It is expected that during this period of accelerated activity various anomalous phenomena, which may be called premonitory phenomena, might occur. Actually, such premonitory phenomena had long been suggested, directly or indirectly, on the basis of laboratory rock-failure experiments, anomalous tilts and strains in the epicentral area, anomalous geomagnetic-geoelectric disturbances, lightning, and anomalous behavior of animals, snakes, fish, and even humans. But none of these was convincing enough to attract the serious attention of seismologists.

One recent development along this line is the dilatancy-diffusion hypothesis of earthquakes; this hypothesis, put forward only two years ago, attracted literally hundreds of scientists into earthquake-prediction research. Although it is still a working hypothesis that should be scrutinized on the basis of more precise data, it gave an important direction to earthquake-prediction research.

This hypothesis says that when tectonic stress exceeds a certain limit, small cracks in the crust open up due to anelastic deformation near the crack tips, resulting in dilation. These open cracks decrease the seismic velocity.

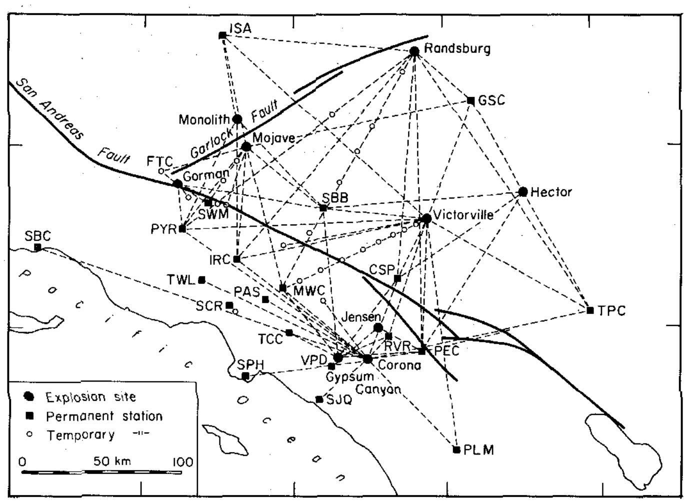
Subsequently, fluid flows from the surroundings into the dilated region increase the seismic velocity again, but at the same time lubricate the rock to trigger an earthquake. Accordingly, if the seismic velocity in a certain area first decreases abnormally and then returns back to normal, it is an earthquake alarm.




Dilatancy model: (1) Stress builds up near a potential earthquake fault. (2) Cracks open up due to anelastic deformation, and the seismic velocity decreases. (3) Fluid flows into the dilated area from the surroundings, thereby increasing the velocity and lubricating the rock to ease faulting. (4) The earthquake occurs. The diagram at the bottom shows the time variation of the velocity corresponding to each stage.

Since the time for this whole process to take place depends upon the size of the affected area, it can also tell us how large the earthquake is going to be. Caltech, along with other institutions, contributed much to this field by documenting such velocity changes for the 1971 San Fernando earthquake and several other smaller earthquakes and by developing a physical model for such a process.

Even if this dilatancy-diffusion model is not correct as it stands, it is quite possible that seismic velocity might still change due to changes in tectonic stress during the period of the accelerated process. In view of this, Caltech has now set up several profiles in southern California along which very precise measurements of seismic velocity are




Explosion sites, mostly quarries and mines (large solid circles), and seismographic stations (the square symbols are permanent stations, the open circles temporary stations) used for precise measurements of seismic velocity in southern California. Velocities are measured along the dashed lines.

repeatedly made to monitor possible temporal changes (above).

So far, only small, but definite, changes have been found for some of the profiles. These changes are much smaller than those reported elsewhere as precursory to earthquakes; at present, it is not clear whether these changes are due to dilatancy or some other causes.

The measurements have just been begun, and we have not yet been able to prove or disprove the dilatancy hypothesis. However, if the dilatancy model proves to be correct, these measurements, if continued with sufficiently close time intervals, will enable us to detect any premonitory velocity changes that take place within the network over an area larger than some 100 km in extent. This spatial extent corresponds to an earthquake the size of the 1971 San Fernando earthquake. □

# A Journey to the Center of the Earth

## Solid State Geophysics at Caltech

THOMAS J. AHRENS

### A real understanding of how the earth "operates" may ultimately lead to prediction and perhaps control of the surface manifestations of its processes

A century has passed since the publication of Jules Verne's prophetic science fiction novels. In that time the adventures of Verne's heroes—Captain Nemo's beneath the sea, and Michael Arden's from earth to moon—have nearly all been overshadowed by the massive technical accomplishments of this century. All, that is, except for Professor Von Hardwigge's, which Verne described in his fanciful *A Journey to the Centre of the Earth*, published in 1864. And it is improbable that we will ever duplicate that feat.

Although the center of the earth is relatively close at hand —a mere 4,000 miles away—because of the very high pressures and temperatures there and the character of the intervening material, it is unlikely that man will ever have direct access to this subterranean world. Reliance on indirect evidence as to its nature is in fact what seismology and geophysics are all about.

During the last decade, the revolution that has swept through the earth sciences has redirected our studies of the earth's interior. It has embodied recognition of the movements of large plates over the earth's surface, their continuing creation from molten rock at the ridges of the oceans, and, finally, their subduction into the earth beneath the great trenches. Specifically, much current research is focused on obtaining data regarding the temperature distribution and mineralogy of the earth's mantle and providing a viable theory for explaining the driving mechanism of plate motions, which are reflected in continental drift.

Aside from our intellectual curiosity as to the nature of the static environment and dynamic processes taking place in the earth's interior, a real understanding of how the earth "operates" may ultimately lead to prediction and perhaps control of the surface manifestations of these processes—the earthquakes and volcanic explosions that can so drastically affect man and his cultural works.

Even with our present limited knowledge of the origins of the vertical motions of the continental crust and the horizontal motions of the sea floor, what we know about the processes of the emplacement of igneous (molten) rocks has already provided important strategies for exploration for mineral raw materials and for continuing supplies of fossil fuels, fissile elements, and geothermal resources. Indeed, in many respects, the future needs of our technologically oriented society will to some degree be met by our ability to understand the nature of, and processes existing in, the earth's interior.

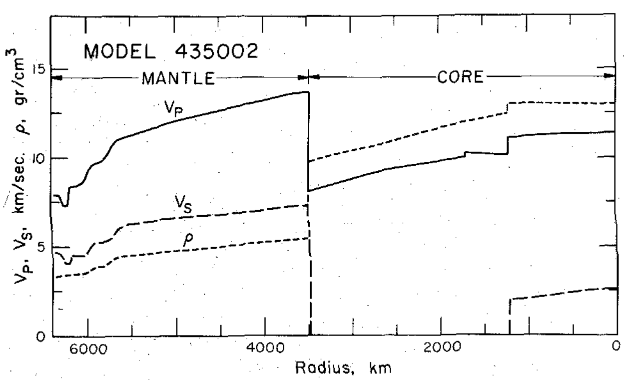
Although the external shape, mass, and moment of inertia of the earth were fairly well established at the time Jules Verne was writing, the fact that the earth has a 3,500-km-radius liquid core (presumably of iron plus lighter elements) was not defined seismologically until 1912, when it was done by Beno Gutenberg, then a young geophysicist working in Göttingen, Germany. The gross picture of the earth's interior that has evolved is that of a liquid outer core (which is the source of the magnetic field) enveloping a small, 1,300-km-radius solid inner core, and a 2,900-km-thick rocky mantle made up of a mineral composition such as $(Mg,Fe)_2 SiO_4$. Only the top of the surface layer, or crust, 10 to 30 km thick, which overlaps the mantle, has been directly explored by man.

Over the last two decades major advances have increased our knowledge of the figure of the earth, particularly the shape of the sea floor, and the global features of its gravity field. Scientists have also made a series of incredibly detailed measurements of the variation of elastic (compressional and shear) wave velocities with depth.

The detailed picture that my seismologist colleagues have given us presents a profound challenge to the solid state geophysicist to provide an explanation of the elasticity and density profiles of the earth in terms of chemical composition, changes of phase (that is, rearrangement of atoms) and reactions between minerals induced by the tremendous pressures and temperatures in the interior of the earth. He must also provide the basic information on material properties—such as thermal diffusivity and viscosity—that is required for theories describing the creation, subsequent horizontal motion, and the final digestion of lithospheric plates into the hot mantle.

To measure such properties as density and compressional- and shear-wave velocity over the range of pressures existing in the earth (reaching 3.7 megabar, or 54 million pounds per square inch at the core) presents a formidable task. The temperatures for the center of the earth have been estimated to run anywhere from 4,000 to 10,000°K. High-pressure apparatus in which minerals can be exposed to static pressures of 30 kilobar (the equivalent of the pressure in the earth at a depth of some 100 km) have provided much important data about the mineralogy and physical properties for the crust and upper mantle.

The current research frontier in solid state geophysics is being pursued by several groups in the United States, Japan, and Australia, using such apparatus. These groups are also testing new equipment that employs a weak solid (such




A recent earth model computed from seismological data by Don L. Anderson and T. Jordan. Data used include classical body-wave travel-time, spectra of the earth's free oscillations, velocities of world-encircling surface waves, and the mass and moment of inertia of the earth.

as sodium chloride) to achieve quasistatic pressures of up to 300 kbar (300 times 14,504 pounds per square inch, or the pressure at a depth in the earth of 1,000 km) using containers constructed of carbides or diamonds. Because of the massive amount of material required to contain such pressures, it is difficult to determine the pressure actually achieved, although chemical reactions, density, and electrical resistance are measured.

At Caltech we have taken a rather different approach to the study of the materials that are likely to make up the lower mantle and core of the earth—shock waves. Fundamentally, generating extreme pressures with shock waves relies on the use of inertial rather than static forces. The pressure gradient between one atmosphere (15 pounds per square inch) and multimegabar (many millions of pounds per square inch) high-pressure environments occurs within the 0.05-mm-thick shock-front zone instead of within a massive static apparatus. The shock waves we are able to induce in minerals—when we achieve the pressures of interest—propagate at speeds of from 2 to 20 mm per microsecond. Thus, typical shock transit times for 0.5-cm-thick samples range from 0.25 to 2.5 microseconds. With high-speed photographic or electronic instrumentation it is possible to observe the shock-front boundary within transparent or semi-transparent crystals; and electrical and optical properties can also be extracted from the shock-induced, high-pressure environments at essentially the speed of light.

Virtually all of our knowledge, direct or indirect, of the pressure-density-energy relations (or equations of state) for a host of elements, compounds, and—most importantly for geophysical purposes—minerals has come from shock-wave research. Many of our earlier studies were carried out using high explosives to generate the shock waves.

During the past five years our group at the Seismological Laboratory has been largely concerned with measuring equations of state of mantle minerals to shock pressures of up to 700 kbar. To date, our principal research tools have been two guns powered by chemical propellants and used to launch projectiles to speeds of nearly three kilometers per second at a series of target materials. In these experiments, projectile velocity and the resultant shock velocity in the target sample allow simple calculation of the shock (inertial) pressure. Since the projectile and shock velocities can be measured to better than one percent, the resulting pressures—as well as the density and internal energy—are determined on an absolute basis to nearly that accuracy. This attractive feature overcomes one of the major difficulties of pressure calibration of static apparatus; however, the price paid is that it is the internal energy and not the temperature that is explicitly determined. Theoretical calculation of the shock temperature turns out, in fact, to be a difficult problem for very large compressions.

We have found over the pressure range available to our present apparatus that almost all the common silicate minerals studied to date undergo very marked phase

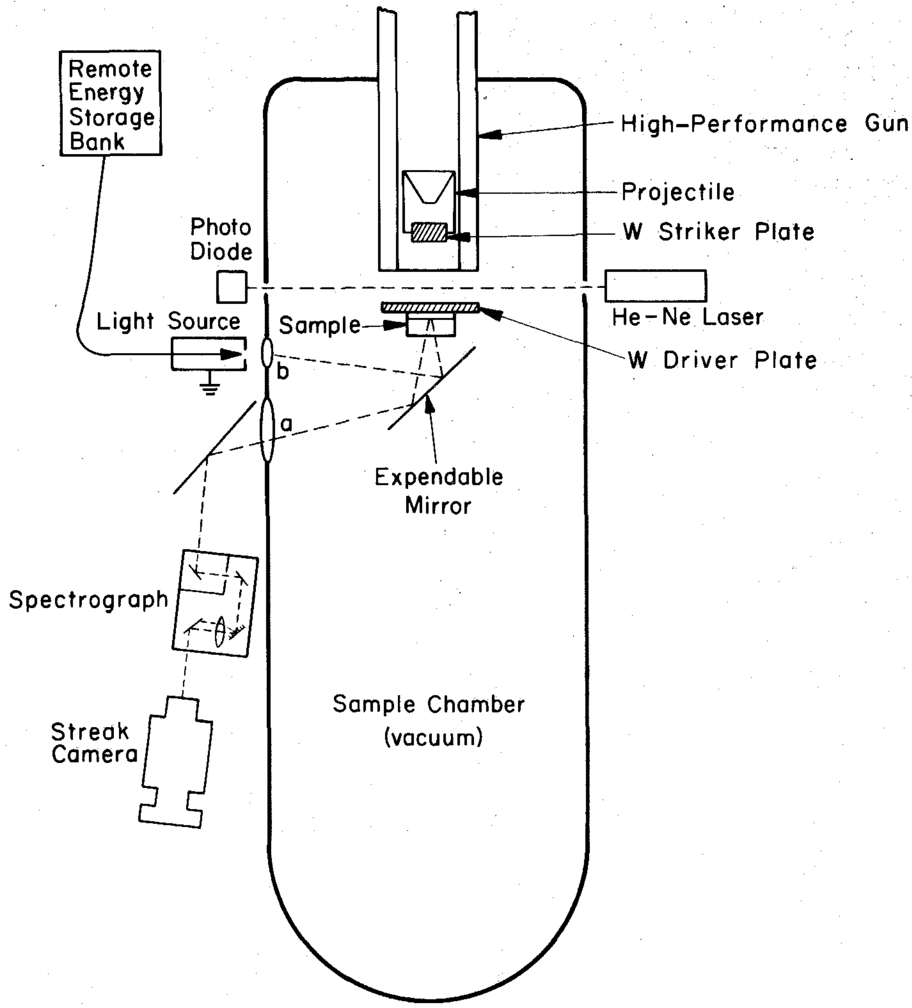
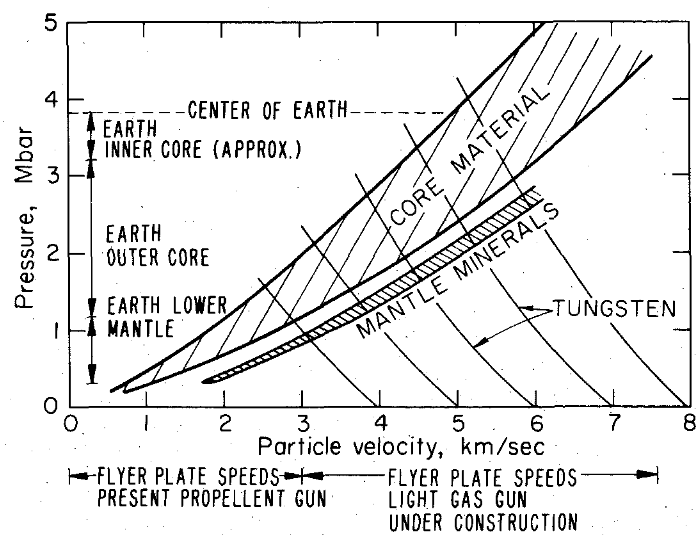



Diagram of the spectrographic system used to measure the adsorption spectra of minerals during shock loading to pressures in excess of 500 kbar. As the shock wave propagates through the sample, light from an intense spark source is reflected from a mirror within the sample and is recorded by a high-speed time-resolving (streak) camera.

changes involving equivalent zero-pressure density increases of from 10 to 30 percent. Major changes in structure with compression have been discovered for such minerals as orthoclase, garnet, ilmenite, and pyrrhotite.

Although the general nature of these new mineral structures was predicted on crystal chemical grounds, we are currently exploring their exact nature to see if the changes can be related to the complicated velocity and density structure of the earth's mantle. This amounts to a whole new field of study—very-high-pressure silicate mineralogy—in which silicon ions are surrounded by six or more oxygen ions instead of the four present in ordinary silicates.

In addition to studying the pressure relations of the major mantle minerals—olivine, pyroxene, and garnet—we are continuing a program of shock-recovery experimentation on a variety of rock-forming minerals. We want to observe, under controlled conditions, the post-shock changes in mineral structure that occur when meteorites impact onto planetary surfaces. Space exploration has demonstrated that meteorite impact is the principal cause of many of the large-scale surface structures on the moon, Mars, and



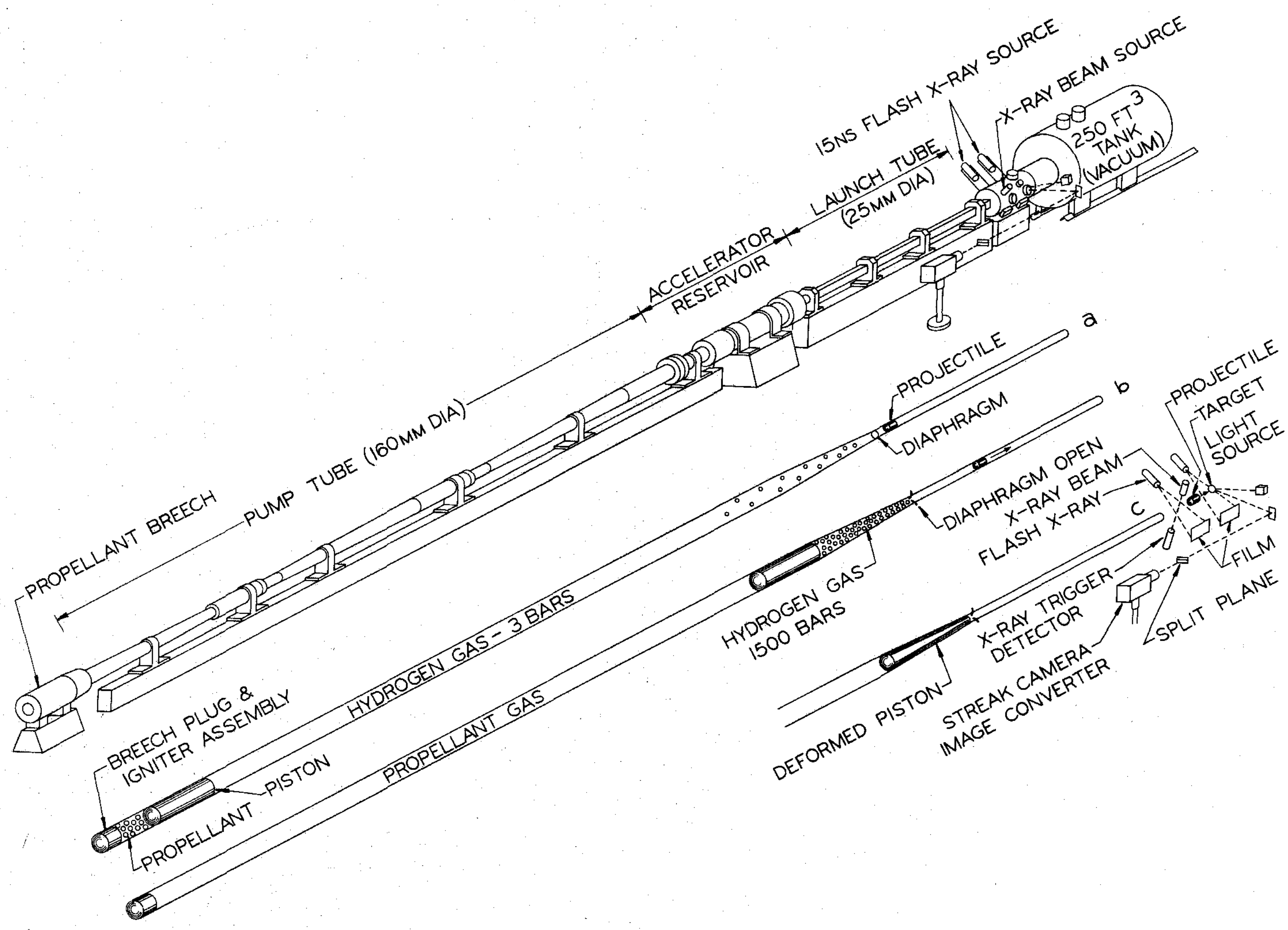

Pressure-particle velocity curves for various mantle and core materials in relation to the performance of propellant and light-gas guns now in use. The intersection of positive-sloping (sample) curves with negative-sloping driver plate (tungsten) curves centered at various projectile velocities determines the induced shock state upon impact. The range of properties for hypothetical core and mantle materials is indicated.

Mercury. Our interest in describing the meteorite impact process has recently led us to obtain the first shock-wave data for lunar rock and soil.

About a decade ago light-gas gun techniques (largely developed at NASA's Ames Research Center and used to launch small models of reentry vehicles into various planetary atmospheres) began to be utilized for the launching of projectiles against targets to generate plane shock waves. The use of these guns to launch impactor plates to speeds of nearly eight kilometers per second has effectively permitted a new region of ultrahigh pressures to become accessible to the laboratory experimenter. Pressures in excess of two megabars in silicate materials and nearly four megabars will now be available for the study of candidate materials of the earth's core as well as for obtaining new insights into the physics of the interior of the major planets.

A diagram of an Ames model launcher, recently converted into a shock-wave apparatus by Norman Keidel and his colleagues in the Caltech Central Engineering Shop, is shown below. This large two-stage apparatus is currently being installed in the Helen and Roland W. Lindhurst Laboratory of Experimental Geophysics, and it will be operated along with the existing single-stage propellant guns by Harold Richeson and David Johnson.

In this way we will be taking a journey to the center of the earth—though only within centimeter-sized samples and for total voyages of less than one microsecond. □




A diagramatic view of the two-stage light-gas gun used for shock-wave research on earth materials. The total length of the apparatus is 106 feet, total weight approximately 35 tons. (a) When the chemical propellant ignites, a 20-kg plastic piston compresses hydrogen in the pump tube. (b) As the projectile enters the high-pressure reservoir section, the diaphragm ruptures and the projectile begins to accelerate down the launch tube. (c) As a result of the deformation of the plastic piston in the high-pressure reservoir, gas pressure is maintained on the base of the projectile as it is accelerated, until it clears the launch tube. After leaving the launch tube, the projectile, which has a tungsten plate in its nose, intersects a continuous X-ray beam and triggers two 15-nanosecond flash X-ray sources. The resulting X-ray shadowgraphs permit the projectile velocity to be measured. When the projectile hits the sample, the streak camera is activated, recording the shock-wave velocity through the sample.

# Understanding Seismograms by Constructing Numerical Models

DONALD V. HELMBERGER

At the turn of the century a number of rudimentary seismographs were constructed. Why scientists became interested enough to obtain proper measurements at this particular time is not clear, but it may have had something to do with the relatively large number of Great Earthquakes that occurred then. A Great Earthquake, magnitude 8 or greater, can be felt over 500 km. With modern instruments, even a relatively small event, such as the Borrego Mountain earthquake of 1968, produces sufficient motion to be recorded at the most distant station. This event, which occurred on the San Andreas fault near the Salton Sea, had a magnitude of 6.4, which is similar to that of the more recent San Fernando earthquake.

Seismograms for the Borrego event as recorded by a World Wide Seismic Seismograph Network (WWSSN) station are shown below. The distance between the seismic event and the recording station is usually indicated in degrees, $\Delta$, as measured at the earth's center. One degree is roughly 110 km along the earth's surface.

Today's standardized instruments, which are later generations of instruments developed at Caltech, are installed around the world and are an important source of data for seismologists. These stations record the three components of motion over two frequency bands: short period (lower trace) centered at about 1 second (SP), and long period (upper trace) at 15 seconds (LP).

Until recently, such seismograms were not used to their full advantage. Conventional measurements included determining the time of first arrival of the seismic wave (for travel-time considerations), the direction of the first motion to ascertain the direction of faulting, and the amplitude of the largest peak in the first few seconds of the short-period vertical motion (SPZ), which is used in assigning a body-wave magnitude to the event.

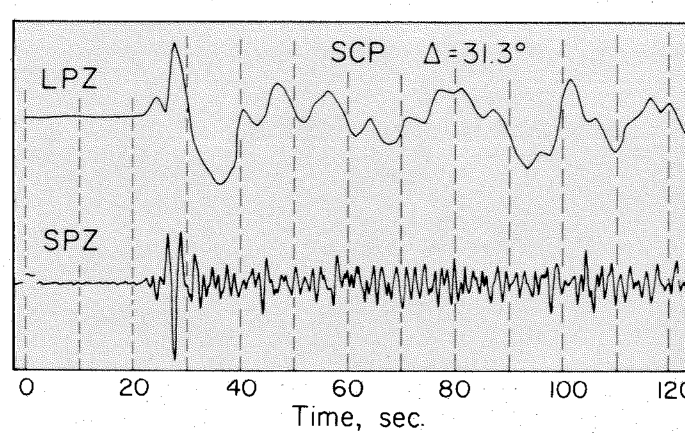
Seismologists in earthquake-prone regions such as southern California have a public responsibility to report immediately the location and magnitude of local events. But this kind of information is only the first step in the scientific study of earthquakes and the interior of the earth. Clearly, the seismograms contain much more information, and we are now attempting to interpret every wiggle. Seismologists are now faced with much stronger demands, such as:

(1) To determine whether a given seismogram was produced by an explosion or by some natural phenomenon;

(2) To determine the detailed structure of the crust, mantle, and core so that solid state geophysicists can speculate on the earth's composition and thermal history, and possibly infer large-scale dynamic processes based on lateral variation in these parameters;

(3) To determine the details of earthquake mechanisms to be used in predicting the nature of the strong motions likely to occur locally during future earthquakes as well as in predicting their occurrences;

(4) To determine stresses in the crust as one step in a program of earthquake prediction.



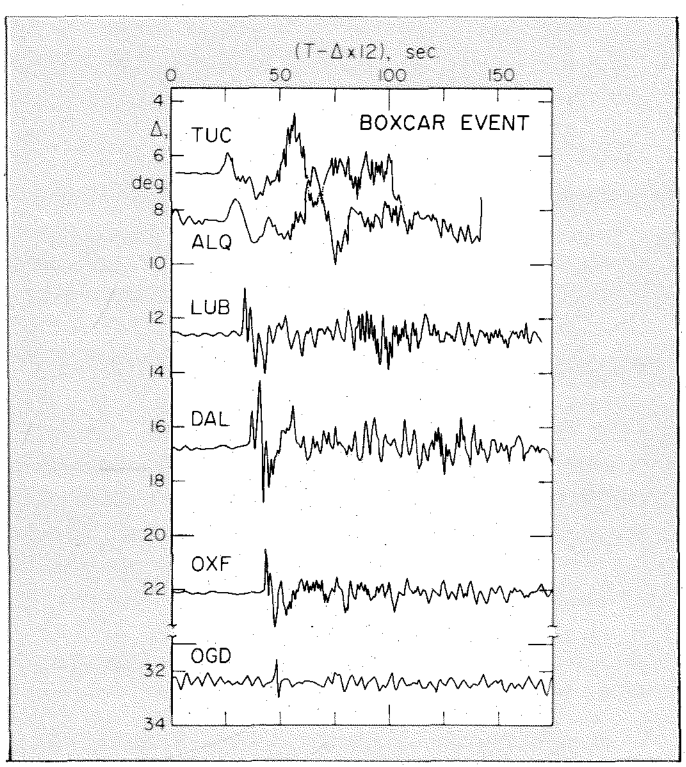

Vertical motion (Z) of long-period (LP) and short-period (SP) waves, recorded by the World Wide Seismic Seismograph Network station at State College, Pa. (SCP), during the Borrego Mountain earthquake of 1968.

**Studying seismograms is the first step in the scientific study of earthquakes and the interior of the earth. Now, seismologists are generating synthetic seismograms to help explain why observed seismograms look the way they do**

These demands require new techniques, and they have created a new branch of seismology. Many modern seismologists are experts in wave propagation and rely heavily on large computers to understand and explain the wiggles on seismograms. Some of these wiggles are due to complexities of the earthquake itself, and some are due to complications inside the earth. Seismologists are now generating synthetic seismograms, simulated inside computers, attempting to explain why observed seismograms look the way they do, and to see what can be learned about the problems I have mentioned. Admittedly, however, we are still developing the necessary theory and techniques.

### Modeling Earth Structure

By studying seismograms produced by known sources, we can discover some of the effects produced by the earth in transmitting the motion from the source to the recording site. Buried nuclear explosions provide an excellent source of energy for this purpose. Since the locations of these explosions and the exact time of their occurrence are well known, they have proved invaluable in earth structure determinations. A profile of long-period recordings from the Boxcar event is given below.

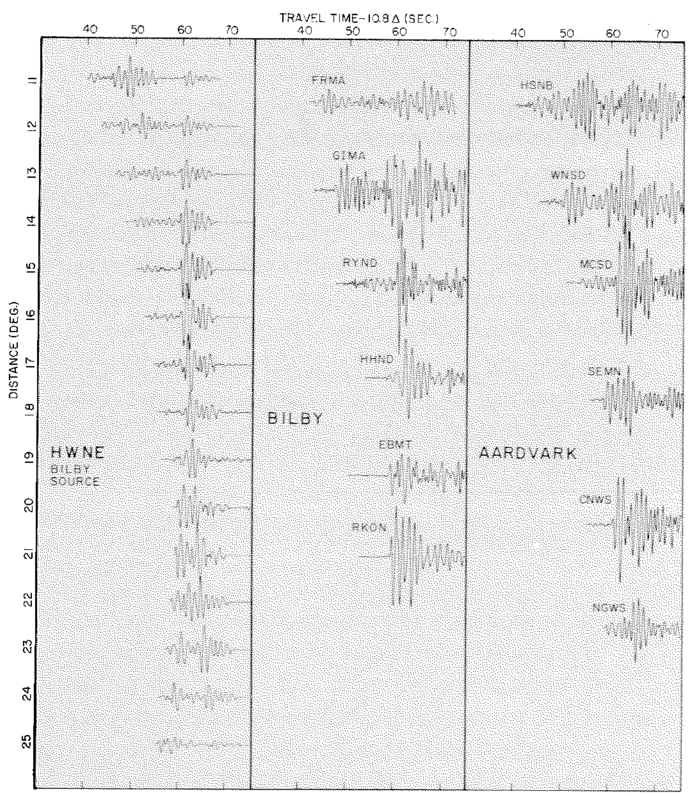



This type of display, common in seismology, shows the variation in amplitude and waveshape as a function of $\triangle$. Distance increases from top to bottom. These recordings are similar to those produced by other explosions fired at the Nevada Test Site. Note the complicated wave forms and how they change with distance.

Explosions, as seismic sources, have been studied extensively in anticipation of a nuclear test ban treaty, and they are reasonably well understood. Essentially, the explosion sends a compressional pulse (P) downward, and this is followed by a surface reflected pulse (pP) with opposite polarity. The separation of these two pulses tells us about the depth of burial. The reflection coefficient that controls the size of pP depends on the takeoff angle (the angle the ray makes with the vertical). For ranges greater than 30°, this angle becomes small, and the phase pP tends to cancel P. The net effect is a pressure pulse that lasts somewhat less than a second, depending on source depth. Further complications are caused by upper mantle triplications (three arrivals at one distance), as will be demonstrated shortly. The absence of short-period energy arriving in the first 20 seconds of motion near 9° is explained by a shadow zone caused by a low velocity zone (LVZ), a feature of the upper mantle discovered by Beno Gutenberg.

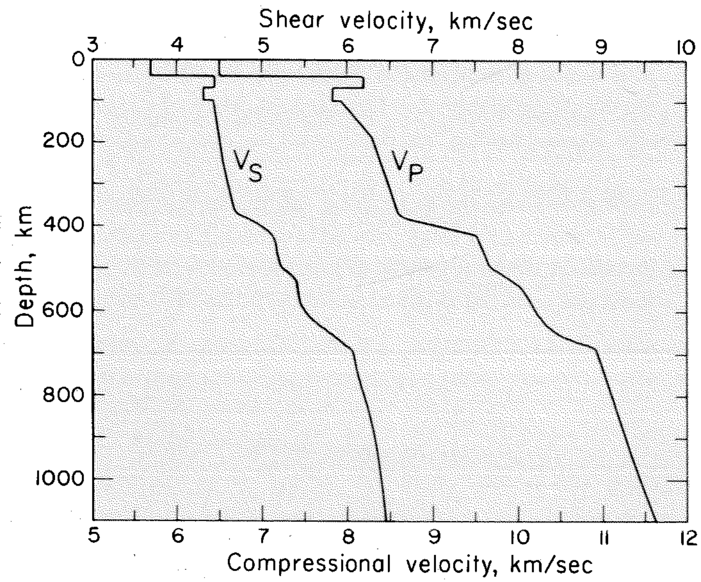
A profile of World Wide Seismic Seismograph Network observations of the "Boxcar" explosion fired at the Nevada Test Site in 1968. Stations represented here are located at Tucson, Arizona (TUC), Albuquerque, New Mexico (ALQ), Lubbock, Texas (LUB), Dallas, Texas (DAL), Oxford, Mississippi (OXF), and Ogdensburg, New Jersey (OGD).

A further windfall produced by nuclear testing has been the installation of the Long Range Seismic Measurement (LRSM) network. These instruments respond well to seismic waves that have a period of about one second. Examples of this type of seismogram from the Nevada Test Site events Bilby and Aardvark are displayed below. At about 15° two signals are readily apparent. The first arrival is small and rather emergent, followed by a larger signal about 12 seconds later.




A comparison of synthetic seismograms (left) with short-period observations made by stations of the Long Range Seismic Measurement Network. The last two letters in each name indicate the state or province where that station is located. "Bilby" and "Aardvark" are two explosions fired at the Nevada Test Site. The synthetics were generated for a particular model, HWNE, using the source function appropriate for the Bilby event. The relative intensities of the various arrivals together with the travel-time information is crucial in model determinations.

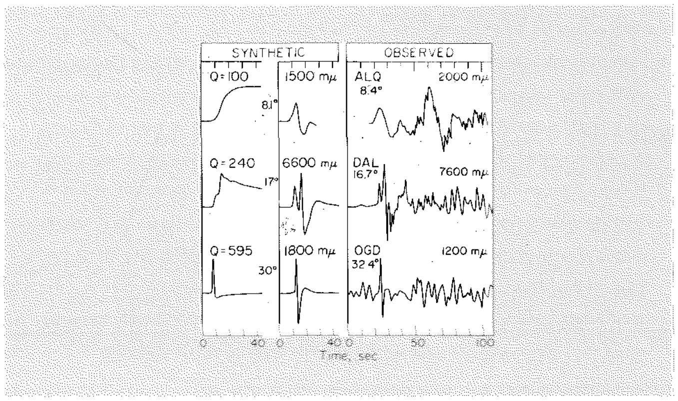
Such a phenomenon is easily explained in terms of upper mantle structure (below). Models containing velocity jumps such as this produce travel-time triplications—that is, multiple signals arriving at the same location at different times. Each of these signals has traveled a different path through the earth's upper mantle. At a range of 15° the first arrival penetrates to a depth of 250 km, whereas the larger second arrival is reflected off the so-called "400 km transition zone" defined by the rapid increase in velocity near that depth. The amplitude and time separation changes with range, producing a rather interesting interference pattern. Unraveling these rays to determine upper mantle structure is no easy task.




Compressional and shear velocities plotted as a function of depth in the earth's mantle.

The determination of upper mantle structure has been a major research effort of geophysicists at Caltech for many years. Several models have been proposed. The variation in models is partly due to lateral differences in the earth and partly due to inadequate data and differences in techniques of interpretation. The earth model presented here has been determined by computing and recomputing synthetic seismograms until they match the observed seismograms. By obtaining this agreement, we learn much about both the earthquake or explosions and the structure of the earth.

Working with many observed seismograms, taken over many paths, we can isolate the features of the seismograms that are due to earth structure. These features require essentially three transition zones in the earth's mantle near 400, 500, and 650 km depth. The sharpnesses of these transitions are still in contention. At the shallower depths, between 50 to 150 km, the earth is known to vary laterally. The velocity model presented here applies to the western United States. Synthetic seismograms for this model assuming the Boxcar source description are below.

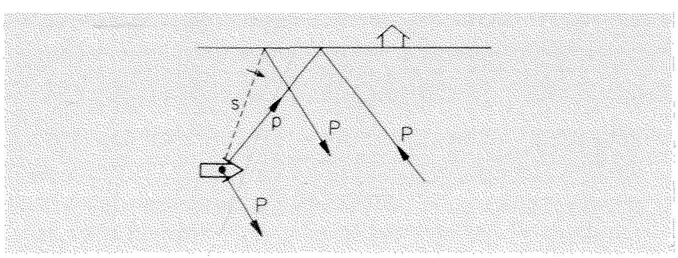



Comparison between synthetic seismograms and observations. The synthetics on the left are the time integrals of the vertical displacement before interaction with the WWSS instrument response.

### Earthquake Source Descriptions

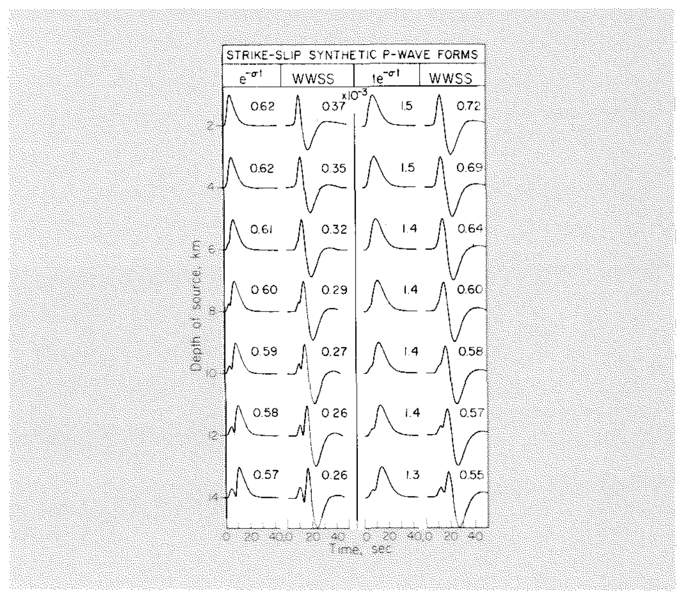
Earthquakes radiate not only P waves but S (shear) waves as well. For this reason, seismograms like that of the Borrego Mountain event on page 26 are more interesting than those produced by explosions. Most earthquakes are quite complicated but are thought to be adequately described by a series of shear dislocations. For example, the two sides of the San Andreas fault are being driven in different directions, with the eastern side moving south relative to the western side. When the stress reaches a critical value, the fault breaks, with one side moving relative to the other side (dislocation), producing an earthquake.

A simplified diagram indicating the seismic waves generated by this type of strike-slip dislocation is given below. Due to the proximity of the earth's surface, essentially three compressional pulses are radiated: P, pP, and sP. These three arrivals interact in a complicated manner, depending on the source depth. Numerical models of these pulses can be generated by assuming various time histories; that is, the time function that describes the motion across the fault.



Displacements produced by a strike-slip dislocation including free-surface interaction, with arrows indicating polarities.

The effective P wave containing the sum of the above three pulses as a function of depth is given below. Two time histories were assumed; the columns on the left are appropriate for a step jump in displacement followed by an exponential decay, whereas in the columns on the right, we supposed a linear buildup followed by an exponential decay. At the shallow depths, all three phases arrive simultaneously. At greater depths, the phase sP falls behind and can be identified as the large second peak. The sizes of the various pulses are controlled by the orientation of the fault. In this particular example, sP is about five times more energetic and overwhelms the other two phases. A comparison of the Borrego Mountain observation at SCP (State College, Pennsylvania) with the synthetics suggests a source depth of about 12 km.




Variation in the effective synthetic P-wave form as a function of source depth.

The synthetic seismograms presented above are examples of the so-called forward problem, the model of both the source and earth structure being assumed. These synthetics prove quite useful in understanding real records, but they can also be used more demonstratively in formal inversion. That is, in solving the inverse problem, given a set of observed seismograms, what source and earth model combination produces the best synthetic fit to the data? Scientists at Caltech's Seismological Laboratory are currently attempting to solve this problem. □

# First Look at Mercury

BRUCE C. MURRAY

**Why go to Mercury? Who needs it? A planetary scientist tells what the voyage is all about**

All of us living today have the privilege of witnessing man reaching out for the first time to examine objects that were nothing more than mysterious points of light to his predecessors. That first look, the reaching out beyond his own planet, is an opportunity offered to just a few generations in all of man's history. I feel that's something to remember when faced by depressing news in the morning newspaper and the evening television program.

The year 1973, for example, in most Americans' minds conjures up images of Watergate scandals, war in the Middle East, the energy crisis, and rampant inflation. Yet it's useful for us to stop and consider that 1973 also was the 500th anniversary of the birth of Copernicus, who first organized man's thoughts about the movements of planets into a rational system. The year 1973 marked the completion of the first half-millennium of the modern age, and 1973—fittingly—was also accompanied by intensive space exploration by Earthlings with unmanned probes to Jupiter, Mars, Venus, and Mercury.

Mariner 10 was launched to Mercury by way of Venus on November 3, 1973. It was not the first probe to visit Venus. Both the United States and the Soviet Union previously have sent probes to that mysterious, cloud-shrouded planet. However, Mariner 10 was the first to photographically explore the close-up appearance of the planet, and did so both in visible and in ultraviolet light. And Mariner 10 was the first probe of any kind to penetrate interplanetary space beyond the orbit of Venus and to achieve a close look at the planet Mercury.

Why go to Mercury? Who needs it? There basically are two kinds of reasons. The first is simple and profound and difficult to quantify: The very act of exploration is a positive, cultural activity. No one knows what is going to be found. Finding out what Mercury, what Mars, or what the moon is really like, enlarges the consciousness of all the people who partake of that new reality. TV pictures are of special importance because they provide a way both for the scientist to discover features and concepts he could not have imagined and for the public to directly appreciate and participate in the exploration of a new world.

But there are more specific scientific objectives as well. For Mercury, the basic—and anomalous—scientific fact is that it is a very dense planet: It contains a great amount of mass for its size. Mercury is a small object, somewhat larger than the moon, but not as large as Mars. Yet, it is as dense as the earth. Thus Mercury, like the earth, must have a large amount of iron in its total planetary composition. Indeed, some years ago it was computed that if Mercury were differentiated chemically the way the earth is, into an iron core and a silicate mantle, Mercury's core would be three-quarters the diameter of the entire planet! (Mercury is 4,900 kilometers in diameter.) The silicate mantle would be a shell merely 500 or 600 kilometers thick. On the other hand, Mercury need not necessarily be differentiated like the earth. Conceivably, it could be composed of silicate and iron phases scattered uniformly throughout its entire body.

In addition to understanding its chemical and physical state, the other paramount question about Mercury is what can be inferred about its history from what can be seen upon its surface. Are there still topographic features that have survived from the time of planetary accretion or early heavy impact? Or have the actions of subsequent atmospheric phenomena or other processes erased those early topographic forms?

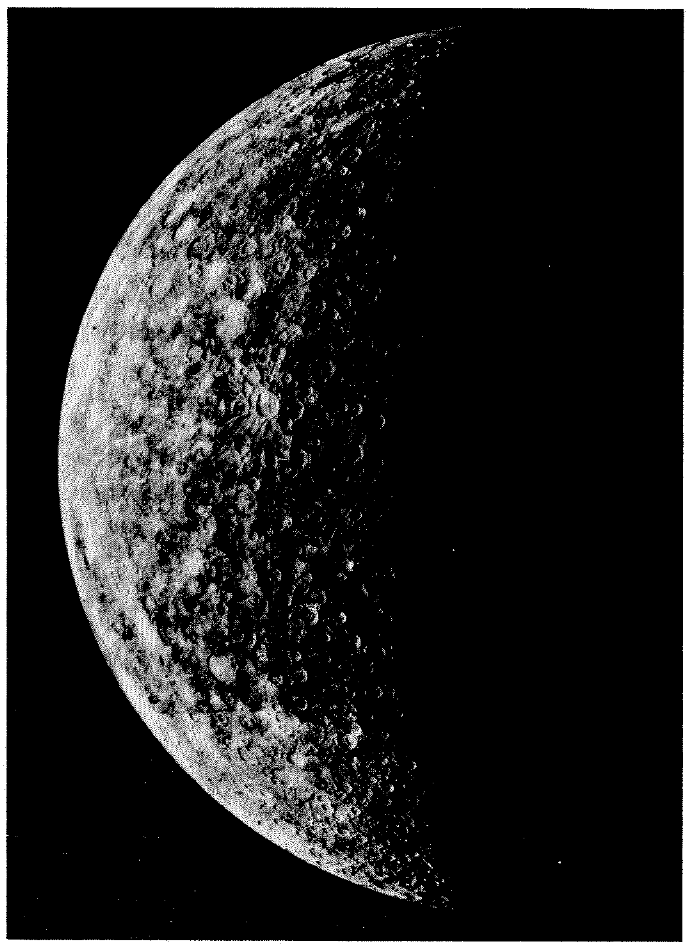
So the guiding objectives of Mariner 10 as a probe, not just for the imaging experiment but for all the scientific experiments, were developed to address two kinds of questions: "What kind of planet is Mercury?" and "What has been its history?" I think we have been rewarded handsomely; rather good answers to both questions have been obtained on the very first exploratory attempt. Of course there is still much scientific debate, but it encompasses a much narrower range of possibilities than might have been the case if Mariner 10 had been a less capable robot.

Before even designing a spacecraft to fly to Mercury, a very large problem had to be overcome. It takes a great deal of rocket thrust to go directly from the orbit of the earth to the orbit of Mercury. A launch vehicle larger than the rocket that launched the Gemini astronauts (Titan) would be needed—far larger than any used previously by the United States for the unmanned probes to Mars.

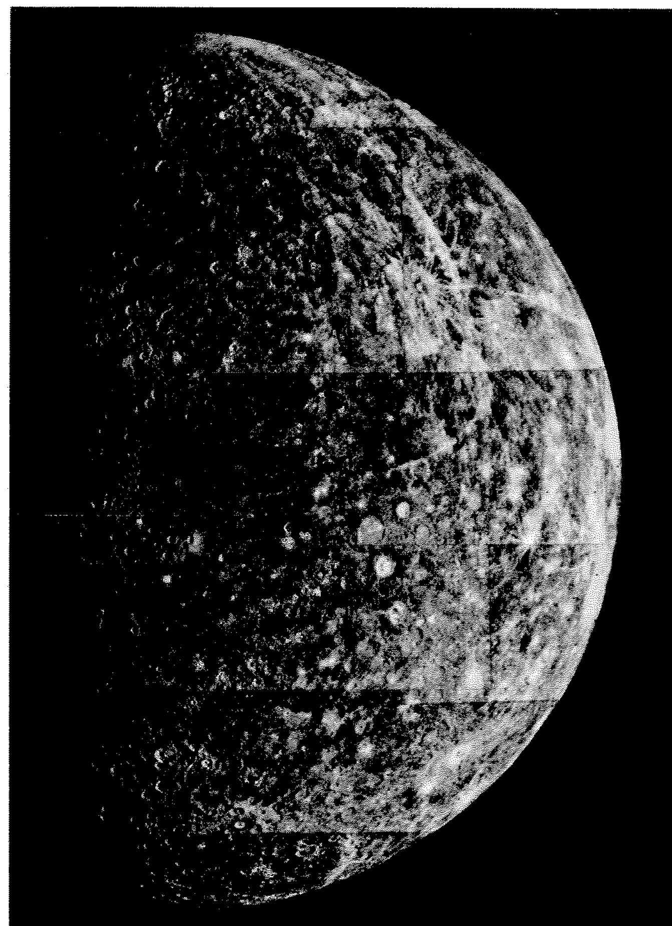
Fortunately for the exploration of Mercury, a clever trick had been thought up some years ago. If a probe passes close to one planet, it can be caught up in a gravitational tug-of-war between the sun and that planet, with the result that the probe is accelerated either in closer to the sun or further outward. Thus, in November 1973, the same kind of rocket (Atlas Centaur) previously used to go to Mars launched Mariner 10 toward Venus. There, a "target" near Venus only 20 miles in diameter was passed at a precise time, and Mariner 10 was diverted by the sun's gravitational pull onto a close passage of Mercury. Had it not been for this energy conservation scheme, there would have been no Mercury flight at all for many, many years, I'm sure. In addition, going by Venus along the way made possible the first exciting photographic exploration of that planet (*E&S*—March-April).

Despite many difficulties, which kept everybody constantly inventing new ways to accomplish old objectives, by the end of March, Mariner 10 approached Mercury and took the first picture about a week before encounter. Fuzzy as it was, it already was slightly better than the best previous pictures taken from the ground. Then the Mariner 10 view rapidly increased in resolution to reveal a heavily cratered surface similar to parts of the lunar surface. Indeed, it looked as though Mariner 10 were encountering the back side of the moon, which exhibits very little of the smooth volcanic plains called maria.

On the other hand, after passing by the closest approach to Mercury on the dark side (below, left) and emerging on the far side, viewing along the terminator, a totally different panorama was seen (below). There the landscape is dominated by vast volcanic plains, flooding large circular

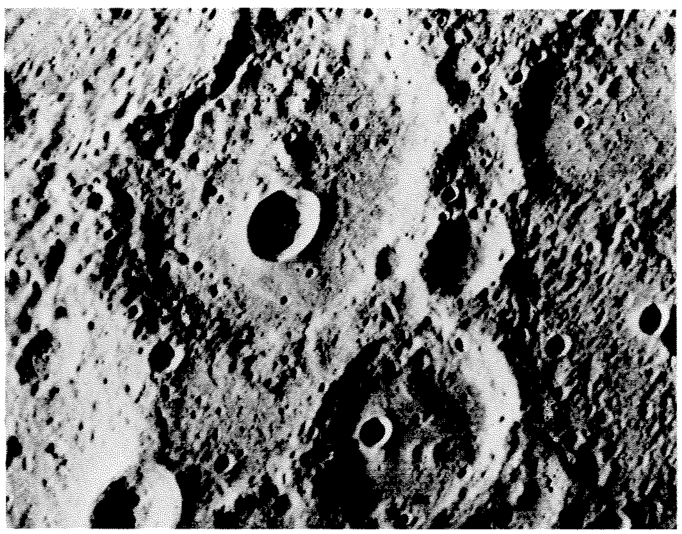


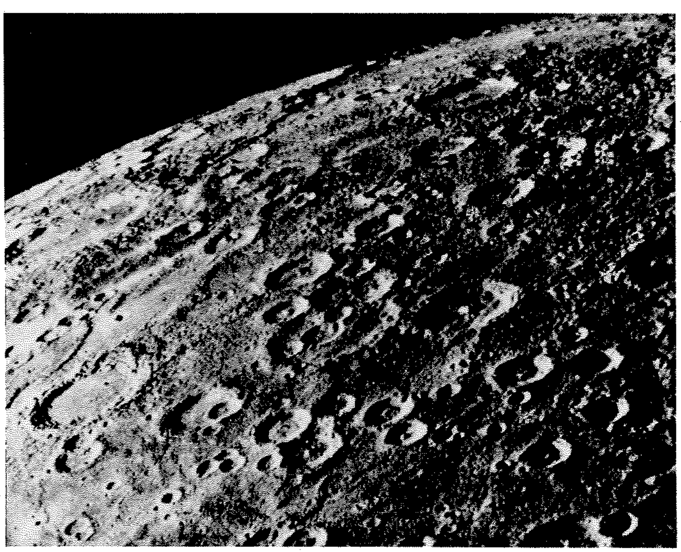
Eighteen pictures, taken at 42-second intervals by Mariner 10's two TV cameras, were computer-enhanced at JPL and fashioned into this photomosaic of Mercury. The pictures were taken on March 29 during a 13-minute period when Mariner was 200,000 km and six hours away from Mercury and approaching the planet. About two-thirds of this portion of Mercury is in the southern hemisphere. The cratered surface is somewhat similar to that of the moon, and the largest craters are about 200 km in diameter.



Taken from a distance of about 210,000 km, this photomosaic of Mercury was constructed of 18 photos taken at 42-second intervals six hours after Mariner 10 flew past the planet. The north pole is at the top, and the equator extends from the left to right about two-thirds down from the top. A large circular basin, about 1,300 km in diameter, is emerging from the day-night terminator at left center. Bright rayed craters are prominent in this view of Mercury. One such ray seems to join in both east-west and north-south directions.

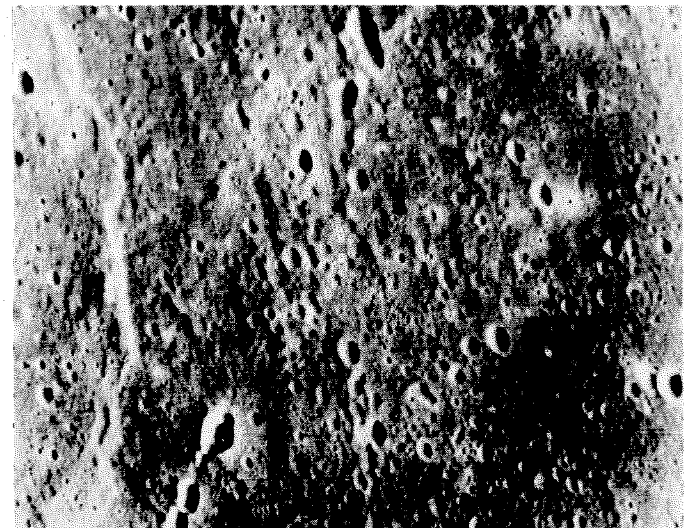
Here the surface of Mercury shows a fresh new crater in the center of an older crater basin. The newer crater (almost centered) is about 12 km across. The picture, which covers an area 130 by 170 km, was taken from a distance of about 20,700 km.

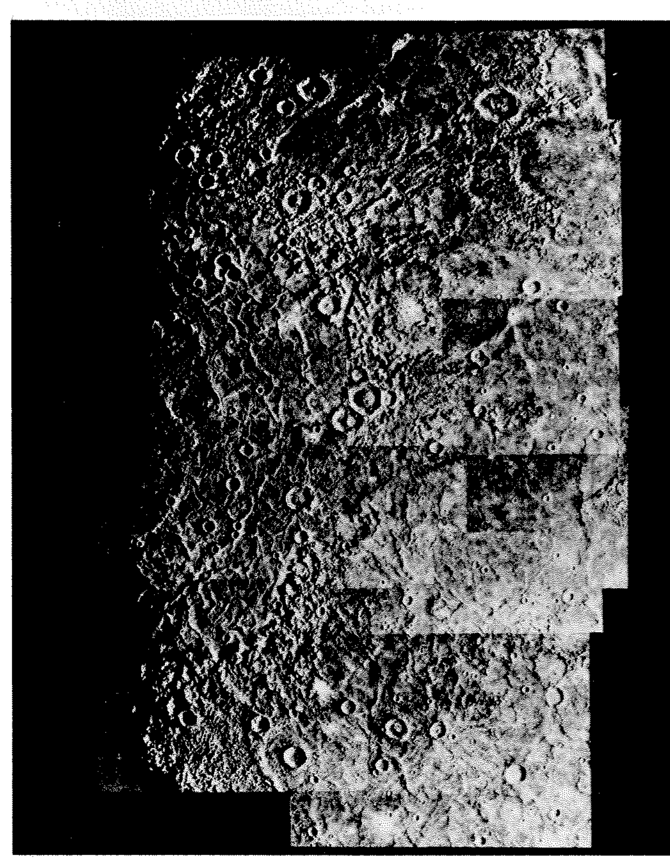




This view of Mercury's northern limb shows a prominent east-facing scarp extending from the limb near the middle of the photo southward for hundreds of kilometers. The linear dimension along the bottom is about 580 km, and the photograph was taken at a distance of about 77,800 km.

Revealing craters as small as 150 meters, this is one of the highest resolution pictures obtained by Mariner 10. The picture is taken from a distance of about 5,900 km and shows an area about 50 by 40 km. In spite of numerous craters in various stages of degradation, the surface is relatively level, contrasting with the abundant relief seen in some views on the opposite side of the planet. The long, narrow area of hills and scarps to the left resembles ridges in the mare material of the earth's moon.





The largest structural feature discovered on Mercury by Mariner 10 is seen in the left half of this photomosaic. It is a ring basin 1,300 km in diameter, bounded by mountains that rise as high as 2 km, and with a floor that is intensely disrupted by fractures and ridges. Similar in size and appearance to the moon's Imbrium Basin, this feature was undoubtedly created by the impact of a body at least tens of kilometers in diameter. Scientists have provisionally named this basin "Caloris" (or hot basin) because of its position near one of the subsolar points when the planet is nearest the sun.

basins, very similar to the lunar mare. Mercury exhibits also the strange asymmetry of the moon (and Mars and earth)—that is, the two hemispheres exhibit very different kinds of topographic features.

Thus the surface of Mercury resembles that of the moon in surprisingly great detail despite the great bulk density differences (3.3 vs 5.4 gms/cm³). What does this have to say about the kind of planet Mercury is and about its history? The fact that there are huge basins that have been flooded with volcanic material, as on the moon, implies that Mercury must resemble the moon down to some appreciable depth—at least the depth from which these volcanic materials originated. Thus Mercury is lunar-like presumably for hundreds of kilometers down. On the other hand, it cannot be of lunar-like silicate composition for more than 500 or 600 km depth and still maintain its gross, earth-like density. Hence, the most plausible explanation of the overall appearance of Mercury as seen in the Mariner 10 pictures is that it is a chemically differentiated planet with a lunar-like silicate zone for the outer 500 or 600 km and a very large iron core for the great bulk of its interior.

The probability of an iron core is also suggested independently by the magnetometer, plasma probe, and charge-particle detectors aboard Mariner 10, which recorded substantial disturbances as the spacecraft passed close to Mercury, of much more magnitude than any experienced in the vicinity of Venus. Conceivably Mercury may not only resemble the earth in its iron core, but may exhibit a very small but permanent earth-like dipole magnetic field as well, although this is still a point requiring further investigation. Thus, the view from Mariner 10 suggests that Mercury is a unique planet, like the moon on the outside but like the earth on the inside.

What has been its history? What can we say, from the pictures, about how Mercury formed and evolved subsequently? First of all, the heavily cratered surfaces, especially as seen on the incoming leg of the trajectory, record topographic forms that could have been created only very early in the history of the solar system, perhaps four billion years ago or more (before any rocks now exposed on the surface of the earth were formed).

Obviously, there have been no subsequent surface processes sufficient to destroy them over that entire time period.

In particular, we can rule out the existence of any tangible atmosphere throughout almost all of Mercury's history. By comparison, even Mars's thin atmosphere is sufficient to modify the appearance of recent impact craters. Secondly, if Mercury is indeed differentiated chemically, that process of separation of the iron phase from the silicates must have taken place very early in its formation, perhaps even during the process of accretion from the solar nebula.

This possibility is in distinction to one traditional view that the earth, at least, accumulated homogeneously, then underwent planetary differentiation later. In the case of Mercury, homogeneous accumulation does not seem to be indicated. The Mariner 10 results, after more analysis, may provide insight into the very early history of the earth itself. Thus, Mariner 10's long reach across space, which magnified by a factor of 5,000 our view of the surface of Mercury, may also carry us back in time, perhaps back further than any previous photographic mission to the planets.

What happens to Mariner 10 after passing Mercury? A very surprising thing! Mariner 10 is in an orbit about the sun that returns to the vicinity of Mercury every 176 days, a duration of exactly two Mercurian years. It will re-encounter the vicinity of the planet every two Mercurian years. The second encounter took place September 21 of this year when we made pictures over the south polar regions of the planet and recorded those areas that were badly foreshortened in the first pass by the planet. It is even possible that some scientific measurements can be acquired during the third passage by Mercury, another 176 days later (March 1975). Not only has man created another minor planet with the mission of Mariner 10, but he has created one that has the peculiar property of being in a resonant orbit with planet Mercury.

Thus, Mariner 10 highlights an unusual period in man's history, in his reaching out to understand his planetary environment. The voyage of Mariner 10 has constituted a very appropriate way to celebrate the first half-millennium of the existence of modern scientific thought, the 500th anniversary of Copernicus' birth. □

# Jupiter's Atmosphere

ANDREW P. INGERSOLL

Why do we study the atmospheres of other planets? The earth's atmosphere is easier to observe. It has more relevance to our lives. And we already know a good deal about it. Routine weather forecasts are now reasonably useful for two days after the forecast is made. Long-term forecasting of average conditions for a month or more may soon become useful. And meteorologists are trying to forecast the climate over periods of hundreds or thousands of years. But there is a basic problem: We have only one earth, and we have only studied it under one set of external conditions. We can't change the earth's orbital position, or its spin rate, or the composition of its atmosphere, and therefore we don't have a complete understanding of how the system would behave under different conditions.

This is where the planets come in. Studying the planets gives us a chance to test our theories in a broader context. Among other things, this testing should give us a better idea of the range of possible climates for the earth and how the earth's atmosphere might respond to changes in some of the external conditions.

Consider Jupiter's atmosphere. Mars and Venus might make equally interesting stories, but cloud patterns on Jupiter are easier to observe than on other planets, and some striking comparisons with the earth can be made. First, there are linear features, the dark belts and light zones that circle the planet on lines of constant latitude. Such a high degree of axisymmetry is not observed on the earth. Second, there are giant circular or elliptical features, like the Great Red Spot, whose lifetimes are tens or hundreds of years. On the earth, the lifetimes of similar features are one or two weeks.

Other differences between the earth and Jupiter that are relevant to atmospheric studies include the immense scale of phenomena on Jupiter—the diameter of the Red Spot is greater than that of the earth, for example; the rapid rotation of the planet—about 10 hours for Jupiter vs. 24 hours for the earth; the probable absence of any solid surface except perhaps at the planet's central core; and the presence of an internal heat source whose integrated intensity may be as much as twice that of the sunlight absorbed by Jupiter. These differences, and others we may not have thought of, are all connected in some way, but the entire puzzle has not yet been assembled.

Part of the work involves building theoretical models, and here it is important to have a good set of criteria for testing such models. First, the theory must be consistent with all reliable observations of the planet. Second, it must be consistent with basic physics—thermodynamics and fluid dynamics as applied to the earth's atmosphere, for instance.

Theories that satisfy these constraints can then be tested in several ways. If the theory is a dynamical one, the resulting flow patterns must be dynamically stable. For example, I once ran some simulations of the Great Red Spot on the computer, and found that the initial elliptical flow pattern quickly broke up into a complicated pattern of waves and eddies. That model was soon discarded.

It is also desirable to have a theory that ties together two or more different types of observations that previously had no logical connection. For instance, from the trajectories of small spots in and around the belts, zones, and the Great Red Spot, it is possible to infer where rising motion is occurring. This inference is made with the help of a theoretical model. The model can then be tested using infrared observations which indicate cloud heights, since high clouds are a sign of rising motion.

Several outcomes are possible: Either high clouds are observed where rising motion is expected, or they are observed where sinking motion is expected, or else there is no correlation. (In fact, the correlation is strong and positive.) Such tests are useful for eliminating theories, and when enough tests are applied together, they can help identify the correct theory.

One test is to consider the long lifetimes of atmospheric features on Jupiter. The only permanent features in the earth's atmosphere are associated with topography—the distribution of continents and oceans. However, most models of the interior of Jupiter—which are based on the inferred properties of hydrogen and helium at high pressures and the observed mass, radius, and moment of inertia of Jupiter—indicate that the interior is too hot for solids to form. This leaves us with the difficulty of explaining how the belts and zones, the Great Red Spot, and other atmospheric features could have existed for so long without any solid structures to hold them together.

Basically, there are two ways an atmospheric flow feature might cease to exist. It might become hydrodynamically unstable and break up into waves and eddies. Or it might simply run down due to loss of energy by mechanical friction or thermal radiation. The stability question is now being studied. There are various possible modes of instability, and thus far it has always been possible to adjust the model so that the flow remains stable when a new mode is introduced. However, an important fact suggests that radiative decay of thermal energy is the ultimate limiting process.

On the earth, the adjustment time for an air mass to reach thermal equilibrium in a new environment is about two weeks. On Jupiter, this time is on the order of 100 years. The difference is due to the large mass and large heat capacity of the cloudy part of Jupiter's atmosphere, as well as the low temperatures and low radiative fluxes. The important fact is that these thermal lifetimes are about equal to the actual lifetimes of atmospheric features on these two planets. Apparently thermal processes, which provide the basic energy source for atmospheric motions, also provide the ultimate mechanism for decay of such motions.

Is the Great Red Spot governed by the same mechanism that governs other flow features in Jupiter's atmosphere? Close-up images of Jupiter taken recently by the Pioneer 10 spacecraft show at least one other spot, about one-third the size of the Red Spot, with a similar appearance. This second red spot is located in the most prominent zone of the northern hemisphere, exactly where one would expect it to be by analogy with the Great Red Spot, which is in the most prominent zone of the southern hemisphere. This observation lends support to the idea that such spots are controlled by and are part of the general atmospheric circulation.

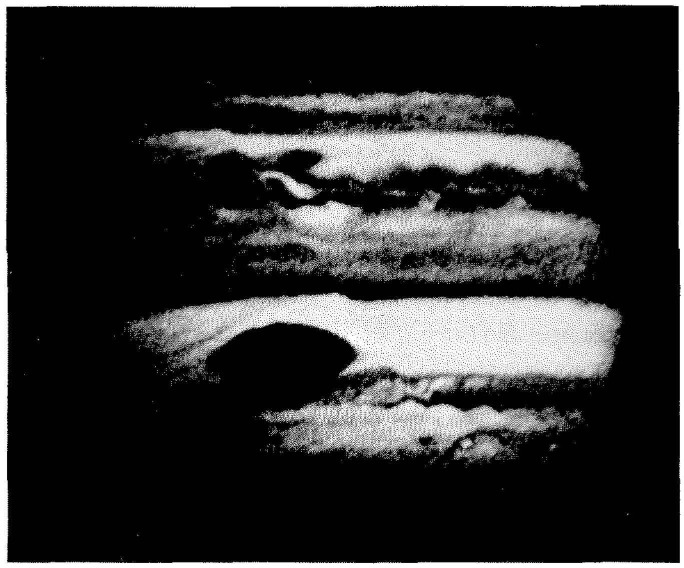
The same conclusion is reached if one compares the Great Red Spot with the belts and zones as in the table below. The zones and the Red Spot are similar in all important respects except for their shape. The belts are the reverse of the zones in all respects. Taken together, these data suggest that the belts, zones, and Great Red Spot are all part of the same phenomenon.

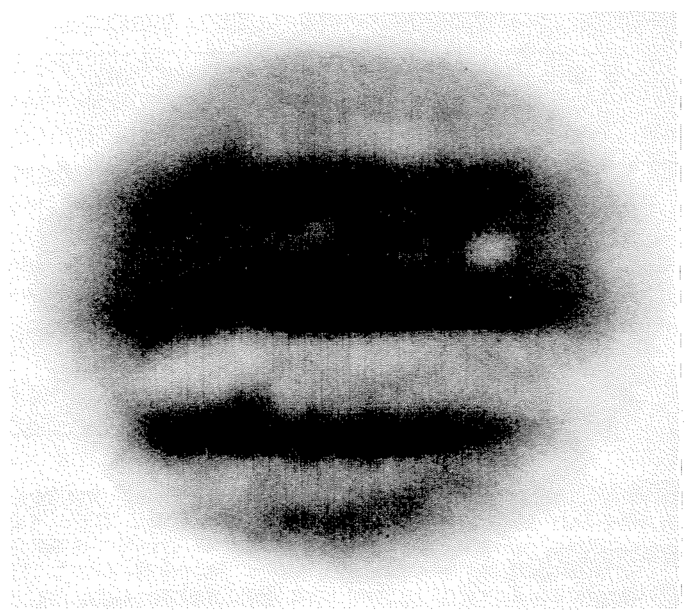
Infrared observations (Column 2), including James Westphal's observations at 5-micron wavelength (page 41), and Pioneer 10 observations at longer wavelengths (lower right), indicate that the infrared emission tempera-

**CLASSIFICATION OF JOVIAN ATMOSPHERIC FEATURES**

| 1. Feature | 2. Infrared | 3. Cloud height | 4. Vorticity | 5. Pressure | 6. Temperature | 7. Vertical velocity | 8. Expected cloud | 9. Color |
|---|---|---|---|---|---|---|---|---|
| Belt | Hot | Low | Cyclonic | Low | Cold | Down | Low, thin | Dark |
| Zone / Red Spot | Cold | High | Anticyclonic | High | Hot | Up | High, thick | White, orange |

**Studying the atmospheres of other planets gives us a better idea of how the earth's atmosphere might respond to changes in external conditions**

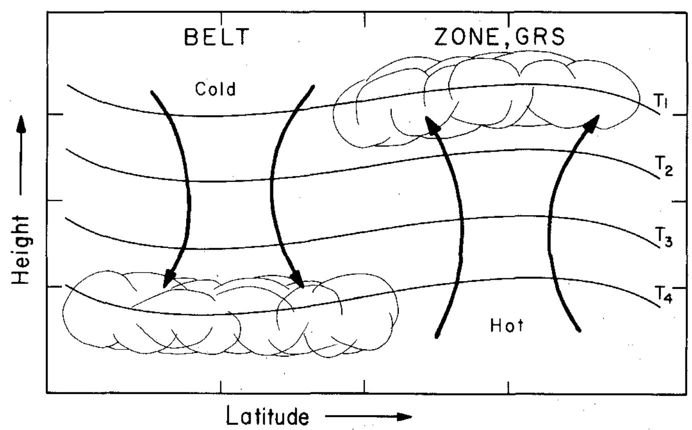




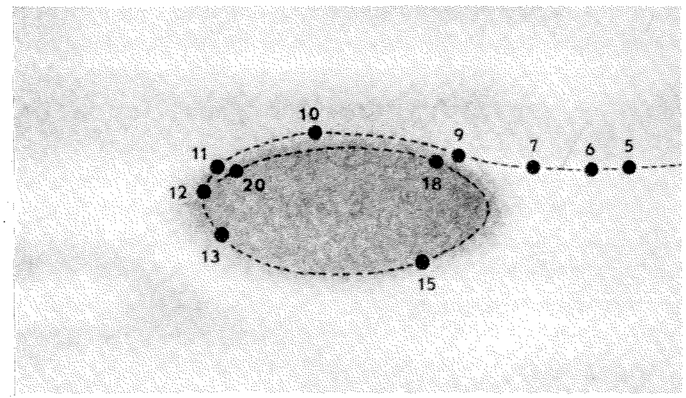
Two images of the same side of Jupiter, taken by the Pioneer 10 spacecraft. At the top is a photograph in visible light (reflected sunlight). The belts and zones are the dark and bright linear features, respectively. In color photographs, the Great Red Spot has a distinct red color which distinguishes it from the belts. The lower picture is an image in the far infrared (thermal emission) at 40-micron wavelength. The belts are darker than the zones or the Red Spot, indicating higher emission temperatures. The Red Spot is light, indicating a particularly low emission temperature.

tures are higher in the belts than in the zones or the Red Spot. This could be due either to the belts being hotter at the same level in the atmosphere, or to our seeing to a deeper, hotter level in the belts than elsewhere. The former possibility can be ruled out on the basis of observed winds in Jupiter's atmosphere, since winds are associated with temperature differences at the same level, and observed infrared temperature differences are much too large to be consistent with observed winds. Thus we are seeing two different levels, which implies high thick clouds in the zones and Red Spot, and low transparent clouds in the belts (Column 3 of table on page 35). The situation is illustrated schematically below.

A separate line of reasoning proceeds from the observed motions of small spots in Jupiter's atmosphere (right). The relative rotation, or vorticity, is always anticyclonic (clockwise in the northern hemisphere, counterclockwise in the southern hemisphere) for the zones and Great Red Spot, and is always cyclonic for the belts (table, Column 4). And because of Coriolis forces due to the planet's rotation, this implies that the zones and Red Spot are high-pressure regions, whereas the belts are low-pressure regions (Column 5)—at least at the level we observe, near the cloud tops. However, high pressures at the cloud tops imply high temperatures inside the cloud, because hot air columns expand upward. (The deep atmosphere below the clouds prevents air columns from expanding downward.) So, from the observed winds, we infer that the zones and Red Spot have higher temperatures than the belts at the same altitudes inside the cloud (Column 6). But high temperatures in this sense imply upward motion (Column 7), and upward motion implies clouds (Column 8), which agrees with the infrared observations showing that clouds are indeed more abundant in the zones and Red Spot than in the belts (Column 3).




A schematic cross-section of a belt-zone pair or a belt and the Great Red Spot (GRS). Heavy curved lines show vertical motion. Quasi-horizontal, wavy lines show the location of constant-temperature surfaces, and are labeled at the right of the figure with $T_n > T_{n-1}$. Clouds are indicated by light lines. Note that the zones and GRS are warmer than the belts at the same height in the atmosphere, although cloud-top temperatures are greater in the belts.




The motion of a small spot in the vicinity of the Great Red Spot in 1968. The numbers refer to successive earth days on which the spot was observed. South is at the top. Typical velocities are about 50 m/s. (Courtesy of New Mexico State University Observatory.)

The colors of Jovian atmospheric features are perhaps the most difficult to explain (Column 9). The principal condensable vapor, ammonia, forms a white frost. However, a variety of colors are possible if the vapor includes complex carbon compounds and elements such as sulfur and phosphorus, which have not yet been detected in Jupiter's atmosphere but which are inferred to be present. If they are present, pressure and temperature changes associated with vertical displacement could then account for differences in color from one region to the next. Generally, a bright white or red color is associated with zones and the Great Red Spot, whereas the belts are always darker and more blue.

All of these arguments suggest that the Red Spot and zones are regions of well-developed clouds, anticyclonic vorticity, and rising motion, whereas the belts are regions of depressed clouds, cyclonic vorticity, and sinking motion. In many respects, the zones and the Red Spot resemble a terrestrial hurricane viewed from outside the atmosphere. Both have low infrared temperatures due to their high clouds, in spite of their warm interiors. And both have anticyclonic circulation at upper levels, in spite of the different conditions at the lower boundaries. The lower boundary is important, however, because a terrestrial hurricane receives its energy from condensing water vapor evaporated off the warm ocean surface. It is not yet clear whether Jupiter's deep atmosphere can supply energy to the Red Spot and zones in an analogous way, from condensation of ammonia and water vapor.

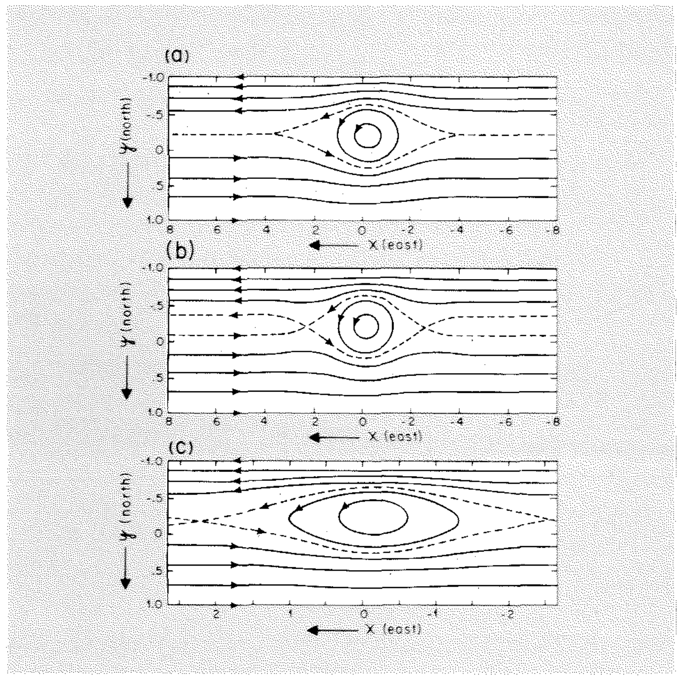
One energy source that can be assessed with data currently available is the radiative exchange at the top of the atmosphere. Because of their extra cloudiness, the zones and the Red Spot lose heat to space at a lower rate than the belts, causing them to accumulate heat inside the cloud. (We assume that heat is supplied from below at a uniform rate.) This interior heat then leads to rising motion and further cloudiness. The belts behave in the opposite way, but they can derive energy from the same process: Depression of the cloud tops leads to an increased rate of cooling, which leads to lower temperatures inside the cloud, sinking motion, and further depression of the cloud top. Thus we have a self-sustaining process, capable of maintaining the flow against dissipation. This process could also be important for terrestrial storms.

To assess this energy source quantitatively, we need a map of the net radiative flux at the top of the atmosphere as a function of latitude and longitude on Jupiter. Net radiative flux includes the infrared emission of the planet—integrated over all wavelengths—minus the absorbed fraction of the incident sunlight. Weather satellites have been making such maps for the earth for more than a decade, but now such a map is possible for Jupiter as a result of the Pioneer 10 flyby (lower photo, page 35). At present, one of my major research activities, and that of graduate students Glenn Orton and David Diner, is the processing and interpretation of the infrared radiometer data from Pioneer 10 with Drs. Guido Münch and Gerry Neugebauer.

The aim of a study of some hydrodynamic models of the Red Spot and the surrounding currents was to see under what conditions such an elliptical feature—with anticyclonic vorticity—could remain stationary and stable in the presence of linear features like the belts and zones. Dissipation, or slow thermal adjustment by radiation, was neglected. No interaction with a solid lower surface was allowed; the motions were introduced as part of the initial conditions and then allowed to evolve freely on the computer. One aim was simply to counter the widespread assumption that you need a solid body at depth to sustain the Red Spot. That aim was satisfied. Stationary flow patterns were obtained, but only if the anticyclonic vortex was imbedded in an anticyclonic linear feature like a zone.

Fortunately, this is consistent with the observed location of both the Great Red Spot and the smaller northern spot in relation to nearby belts and zones. In other words, the model says that only certain locations are permitted for anticyclonic vortices like the Red Spot, and these locations appear to be the ones where such features are observed.

Steady hydrodynamic models of the Great Red Spot and neighboring currents. Arrows show the direction of flow. In (a) and (b) the x axis is compressed by a factor of 3. In (c) the central portion of (b) is shown on an uncompressed scale. The model illustrates a free atmospheric flow; no interaction with a solid lower surface is assumed.



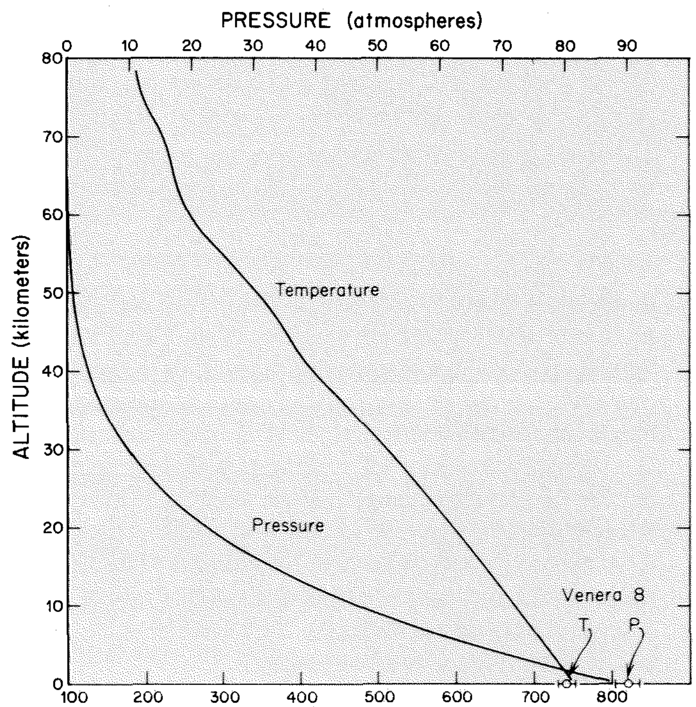

Another model (above) was set up in a frank attempt to duplicate as many features as possible of the observed motion of small spots in the vicinity of the Great Red Spot (page 36). Some interesting features of the model that are observed around the Red Spot are: the cusped tips at the leading and trailing edges (a) and the streamline (b) which crosses itself, enabling small spots approaching the Red Spot to change latitude and recede away in the opposite direction. In a numerical check of this model, if we choose the length scale of the features to fit the observations and use the radius and rotation rate of Jupiter, we obtain velocities for the currents which are also in agreement with observation.

With other theoretical models, my colleagues and I are trying to account for the observed widths of the belts and zones, as well as their observed east-west orientation. Some of these models have been successful; in fact, there are now several competing models, each of which depends on some parameters that have not yet or cannot yet be measured. The greatest uncertainties are associated with conditions below the clouds. What is the temperature profile at depth? Are there significant large-scale motions? Is there a solid surface at some level? These and other questions will be answered in the coming years. With the answers, we will better be able to understand Jupiter, and thereby to put the earth in a broader perspective. □

# A Penetrating

DUANE O. MUHLEMAN

**Earth-based radio observations are a powerful tool in our investigation of the solar system. Here's what a radio astronomer "sees" when he looks at Venus**




These curves show the temperature and pressure profiles of the Venus model atmosphere. The earth's atmosphere is very crudely similar to Venus's at about the 50-km level. The Russian (Venera 8) surface measurements are indicated by the circles.

All objects in the solar system emit radio noise. The primary mechanism is simply blackbody radiation that depends on the absolute temperature of the object, although other emission mechanisms have been discovered, particularly for Jupiter. Since the temperatures of solar system bodies range from about 50 to 800 degrees Kelvin, most of the blackbody radiation is in infrared, rather than radio emissions. Thus, radio astronomers must be contented to work with much weaker radiation fields.

The primary advantage in studying the radio emission of objects is that long-wavelength radiation has great penetrating power, which is well demonstrated by the fact that your pocket radio works rather well in the sub-basement of a concrete Caltech building. For example, when we detect the radio emission from the moon at a wavelength of 50 centimeters, the effective emitting layer in the moon's soil is about 7 meters beneath the surface.

The importance of this phenomenon is more dramatically illustrated when we consider a planet such as Venus, which has a thick atmosphere. At a wavelength of 50 cm, nearly all of the emission from Venus arises in the first few meters of the planet's surface; but at much shorter wavelengths—say in the infrared—all of the emission arises from altitude levels greater than 50 kilometers. Thus, for Venus we can select a particular atmospheric layer for study by choosing a particular radio wavelength of observation.

Radio emission from all of the planets (except Pluto), the moon, the sun, and one of the major satellites of Jupiter has been studied at Caltech's Owens Valley Radio Observatory since the founding of the Observatory in 1959. In the last 10 years most of the investigations of the solar system objects have been carried out by Glenn Berge,

# Look at the Planets

senior research fellow in planetary science and radio astronomy, and myself, with the aid of numerous graduate students. The facilities of the Owens Valley Radio Observatory have been of major importance because of the interferometer, consisting of the 130-foot antenna and two 90-foot antennas that can be moved on tracks. We achieve east/west spacings of over 1 kilometer and north/south spacings up to half a kilometer.

One of the obvious disadvantages in working in the radio spectrum is that the beam widths of antennas become very large at relatively long wavelengths. No single antenna in existence has a beam size smaller than Venus—the largest planet in the sky. Therefore, spatial resolution must be achieved by some trick such as interferometry. Stated crudely, an interferometer operates as though it consists of two (or more) pieces of a giant antenna whose diameter would equal the antenna spacing. It isn't sufficient to just have two spaced antennas; they must be wired together so that they operate coherently. In this case the analogy to a giant antenna is complete.

Rather than listing Caltech's contributions to our knowledge of each solar system body, I will restrict my remarks to Venus—the radio astronomer's ideal target. Venus, of course, has received major attention in the space program during the last decade as well as from earth-based observers. I will not attempt to review all of this history, but will concentrate on the intimate relationship between all of these efforts and the contributions from radio science.

Modern investigations of Venus began with the measurement of radio flux from Venus at 3 cm by workers at the Naval Research Laboratory in the middle 1950's. They reported that if the emission was blackbody radiation then the temperature of Venus must be about 600°K! This result was very hard to understand, taking into consideration the similarities beween the earth and Venus and the fact that Venus is really not much closer to the sun than the earth is.

Since a measurement at a single wavelength cannot tell you the physical mechanism behind the radiation (it could have been lightning discharges, a hot ionosphere, or many other things), a second measurement at a longer wavelength was quickly made. The result was the same, about 600°K, which strongly supported the blackbody hypothesis. By 1960 enough of the Venus spectrum had been measured to convince most radio astronomers that Venus was indeed that hot. However, many people remained skeptical until the Russians actually flew a thermometer to the surface of Venus.

In 1960 Alan Barrett of MIT studied several widely different models of Venus and its atmosphere—one of which we now know is essentially correct. The model assumed that Venus had a pure $CO_2$ atmosphere and, in order for the numbers to agree with the measurements, the surface pressure must be about 100 atmospheres. Unfortunately, no one knew which of Professor Barrett's models was correct at that time.

Great strides at settling the issue were made in 1962 at Owens Valley by Barry Clark, then a Caltech graduate student and now at the National Radio Astronomy Observatory. The difficulty was in being sure that the equivalent blackbody temperature of the radiation corresponded to the true temperature of the atmosphere and surface. Radiation flowing through a surface interface has its polarization altered. In particular, for emission at the Brewster angle (about 50 degrees from vertical for Venus), the emerging radiation is nearly plane polarized even though the blackbody emission under the surface has random polarization. Furthermore, emission from the gases in the atmosphere is completely unpolarized. Barry Clark's measurements with the interferometer showed that the 10-cm radiation was polarized in this manner, proving that this radiation was coming from the subsurface of Venus and that Venus was indeed hot—about 700°K after correcting for the surface emissivity.

I should point out that before radar echoes were obtained from Venus by a group at JPL (including myself) it was not certain that Venus even had a solid surface. The radar measurements showed that the atmosphere, while thick, was still partially transparent at a 12.5-cm wavelength and that the surface material was probably ordinary rocks and soils (as opposed to a universal sea of oil or whatever). To this day I don't understand why so many people had to wait for a spacecraft landing on the surface before becoming convinced about the unusual properties of Venus.

During the last seven or eight years Glenn Berge and I, joined more recently by a graduate student in planetary science, Glenn Orton, have made high-resolution observations of Venus at many wavelengths. Our goal is to develop a model of the atmosphere and surface that is consistent with all available observations of Venus. Our measurements are primarily determinations of the radii of the effective emitting layers in the atmosphere, as well as the brightness temperatures both as a function of wavelength and the surface polarization.

We have combined our observations with radar measurements of the reflecting power of Venus, which is also a function of wavelength due to the varying atmospheric absorption. We have also used measurements of the refractive index of the atmosphere as a function of altitude made during the passage of Mariner 5 behind the Venus atmosphere.

In this experiment, investigators at JPL measured the alteration of the Doppler shift of the Mariner communications signal as the ray path moved deeper into the Venus atmosphere. These measurements reached down to an altitude of 35 km, at which point the signal was cut off by critical refraction; i.e., the density gradient is so great in the Venus atmosphere that the curvature of the ray approaches the radius of Venus, and no signal can pass through the atmosphere from the spacecraft to the earth. These measurements are sensitive measures of the atmospheric density (if the chemical composition is known).

We know very little about the composition other than that more than 90 percent of the atmospheric gas is $CO_2$ and that there are *traces* of water vapor, HF, and HCL. In our model calculations we assumed that the main thermodynamic structure of the atmosphere is controlled by the $CO_2$ and the nitrogen that surely must be present.

In order that our model fit all of the diverse observations, we find that the atmosphere must consist of $96 \pm 3$ percent $CO_2$ with the remainder essentially all nitrogen. Perhaps more importantly, we find that, without the trace gases present, this atmosphere would be deficient by almost a factor of two (1.95) in its ability to absorb radio waves. Thus, the trace gases may not be very important in determining the physical structure of the atmosphere, but their presence is very important in controlling the planet's emissions. Undoubtedly, the complete list of trace gaseous compounds is much larger than that given above; e.g., there is rather strong evidence that the clouds of Venus contain considerable quantities of sulfuric acid. The immediate goals of new research on Venus are centered on the detection of the remaining chemical constituents of the atmosphere and surface.

How does our latest model compare to "ground truth"? The Russian Venera 8 measured the temperature and pressure for a few minutes while it sat on the Venus surface. These values are shown in the drawing on page 38, along with our temperature and pressure profiles. Since no one knows whether the Venera 8 was parked on a mountain or in a deep valley, we had to assume that the measurements were made at the mean surface of Venus. (We have determined this surface to have a radius of $6051.2 \pm 1.0$ km.) The agreement with the model is very good.

We have learned a great deal about Venus. We understand the gross structure of the atmosphere and surface. Recent measurements of the radio occultation by Venus of Mariner 10 have found several cloud layers formed by unknown substances high in the atmosphere. It is the investigation of the chemistry and thermodynamics of these structures that lies ahead. Perhaps when this step has been accomplished we will be able to understand why Venus is so hot and why enormous quantities of $CO_2$ are in the atmosphere instead of being tied up in the surface materials as on the earth. And finally, perhaps we can solve the biggest puzzle of all—why Venus is so deficient of water in comparison to the earth.

I have told the story of Venus from the standpoint of a radio astronomer. Many equally interesting and complex objects exist in the solar system for us to study. We must improve our equipment and build new systems that can investigate the millimeter spectrum where the emission is stronger and many atmospheric gases have a rich microwave spectrum. Earth-based radio observations will remain a powerful tool in the investigation of the solar system. □

# Taking Jupiter's Picture in the Infrared

JAMES A. WESTPHAL

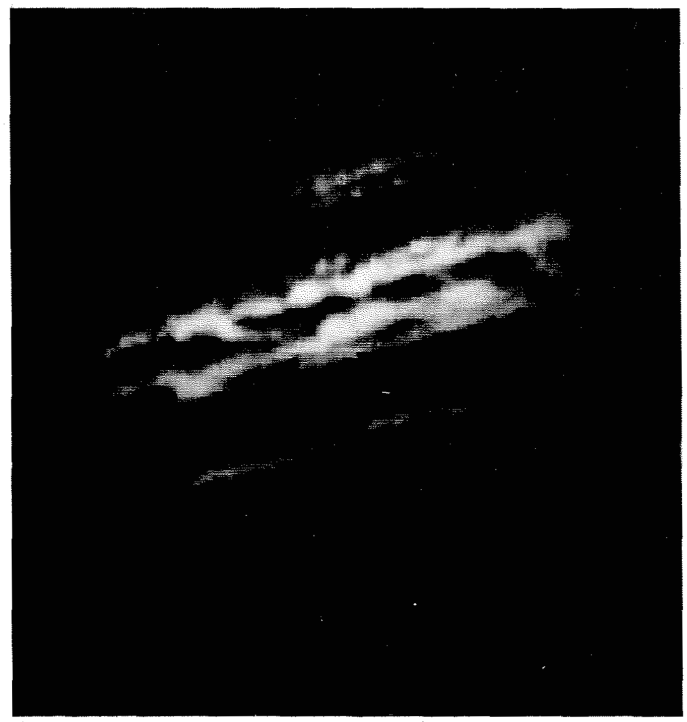
**These unusual pictures of Jupiter may lead to a more complete knowledge of the meteorology of the planet**

A new addition to the 200-inch Hale Telescope at Palomar Mountain has allowed my colleagues—Richard Terrile, Keith Matthews—and me to collect some very useful and spectacular "pictures" of Jupiter. These pictures are made by slowly moving the image of the planet over a very small photocell in a series of north-south "scans" while moving the whole 200-inch slowly eastward across the planet, thus building up a picture much like that produced by a television camera.

The new addition is an electronically controlled Gregorian secondary mirror. It is attached to the prime focus pier of the 200-inch, which can be "wobbled" in step with an electrical signal sent up from the Cassegrain observing station in the cage on the bottom of the telescope tube some 65 feet away. The Gregorian mirror focuses the light from the planet collected by the 200-inch mirror onto a liquid nitrogen cooled photocell that is sensitive to light with a wavelength about 10 times longer than visible light.

This photocell, also a new development, converts the 5-micron-wavelength infrared light into a very small electrical current, which can be amplified, converted to a digital value, and recorded on a digital tape recorder. The tape can be read directly by the Caltech IBM 370/158 computer, and the 16,384 numbers representing the 5-micron light intensity at each of 16,384 points in the picture can be corrected for various calibration factors by the computer. A new digital tape can then be written by the computer, and it can be played back in our laboratory to produce a photographic picture of the planet at 5 microns.

Earlier studies of Jupiter at 5 microns at the Hale Observatories and at the University of Arizona had shown that the 5-micron energy was coming from very localized areas of Jupiter. We had concluded that these were probably places where the visible cloud deck in the Jovian atmosphere was unusually thin or perhaps had holes through which we could see the 5-micron infrared light from the hotter lower clouds or haze below the clouds.



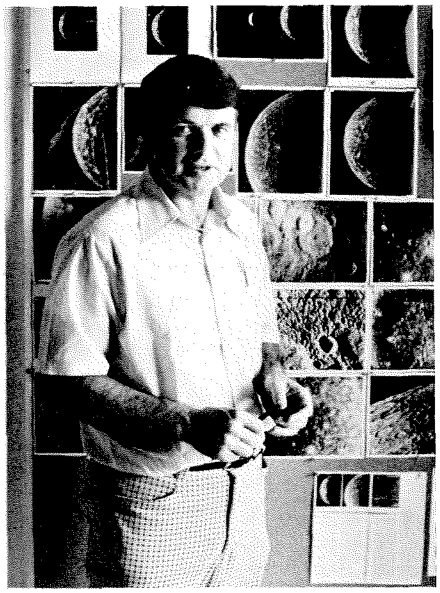
With the "wobbling secondary" and the new photocell, we were able to make a picture every 168 seconds, with a sharpness limited only by the turbulence in the earth's atmosphere. Since last fall we have collected over 500 of these pictures along with occasional Kodachrome color pictures to compare the visible features with the 5-micron pictures, as in the examples above.

It is easy to see that the dark features (which are blue or purple on the original Kodachrome, left) are regions of high 5-micron intensity (bright regions on the 5-micron picture, right).

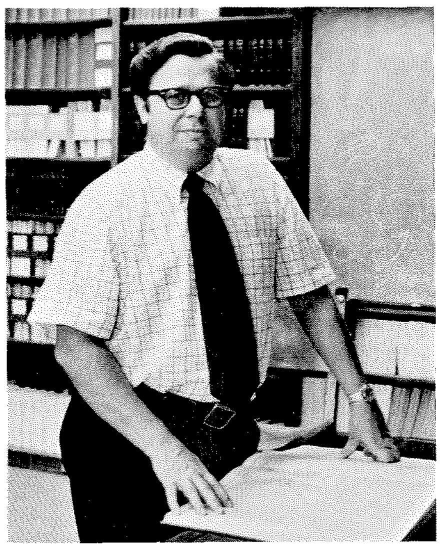
If indeed the 5-micron light is coming through holes in the clouds, it should be possible to learn something of the nature of these holes—perhaps their sizes, shapes, and depths.

To do this, we consider not only the amount of light, but the way in which the light from an individual hole changes as the hole moves across the line-of-sight to the earth as Jupiter rotates about its axis each 10 hours. Richard Terrile is studying this problem by comparing models of the clouds with the observations by using a computer.

We are now extending this technique to studies of other planets (so far, Venus and Saturn), and to other wavelengths. We have great hopes that such high-resolution pictures will lead to a more complete knowledge of the meteorology of the planets. □



Murray



Muhleman

**Bruce C. Murray**

Bruce Murray, professor of planetary science, earned his undergraduate and graduate degrees at MIT in geology. He has been on the Caltech faculty since 1960, becoming increasingly interested in applying his training to the study of the surfaces of the moon and planets. He has been especially involved in close-up photography from Mariner spacecraft. Mariner 9's flight to Mars provided Murray with the opportunity to organize a lively pre-mission seminar and post-mission book, *Mars and the Mind of Man*. Most recently he and his associates in Caltech's Space Photography Laboratory have been concerned with the probe by Mariner 10, which photographed the clouds of Venus and the surface of Mercury. "First Look at Mercury" on page 30 is adapted from his May 13 Watson Lecture in Beckman Auditorium, in which he reports some of the scientific findings of the flyby.

**Andrew P. Ingersoll**

Andrew Ingersoll, associate professor of planetary science, may not be officially in the business of communication, but he has considerable ability to convey by precept and example the message that science is fun. Just ask those who heard him speak on that subject at 1973's freshman orientation at Catalina, for example. He studies oceans and atmospheres and likes to spend his summers at the Woods Hole Oceanographic Institution. His specialty is planetary atmospheres, especially the large weather systems on other planets, such as the belts, zones, and red spots of the giant planet Jupiter. Understanding those, he says in "Jupiter's Atmosphere" (page 34), may make it possible to put the earth in broader perspective.

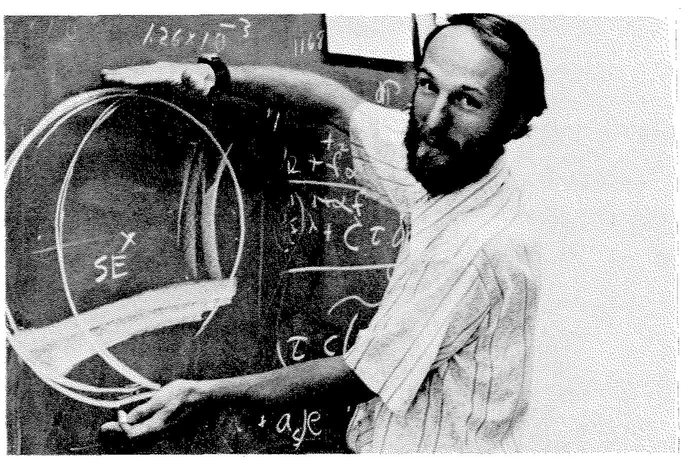
**Duane O. Muhleman**

Duane Muhleman, professor of planetary science and staff member of the Owens Valley Radio Observatory, received his BS in physics from the University of Toledo in 1953 and his PhD from Harvard in 1963. He spent much of the intervening time as a research specialist in radio sciences at JPL, and he is still a consultant there. Muhleman was a visiting professor of astronomy at Cornell University in 1966-67, and he has been a member of the Caltech faculty since then. In "A Penetrating Look at the Planets" on page 38, Muhleman discusses some of his scientific findings as a radio astronomer, with particular attention to his research on Venus.

**James A. Westphal**

When paleoecologist Heinz Lowenstam had the problem several years ago of how to keep some deep-ocean animals alive in a tank, he consulted James A. Westphal—one of a long line of virtuoso instrument designers at Caltech. Westphal, now associate professor of planetary science and staff member of the Hale Observatories, suggested using stainless steel, lucite, eight-inch-long hypodermic needles, and some special pumps—thus solving the problem. Westphal was recruited from industry after he worked with another Caltech professor, Hewitt Dix. They used Dix's VW bus, a miniature seismo lab, to map the deep layers of the earth. His latest work is using an ultrasensitive infrared photocell detector attached to the 200-inch Hale Telescope. In "Taking Jupiter's Picture in the Infrared" on page 41, Westphal reviews some of the capabilities of the new instrumentation.

*continued on page 45*



Ingersoll

Westphal

# In This Issue

*. . . continued*

**Glossary**

If this issue seems to be dabbling a tentative toe in the esoteric waters of the metric system (in most cases not printing equivalent English figures when our authors have expressed themselves metrically), it's at least partly a matter of a space crunch. But we also think it's time to face up to the infiltration of metric measurements and terms into our everyday lives. For the benefit of those who need some help with the conversions, here are a few basics:

| | | |
|---|---|---|
| 1 micron | 0.001 millimeters | 0.000039 inches |
| 1 millimeter | 0.001 meters | 0.039 inches |
| 1 centimeter | 0.01 meters | 0.39 inches |
| 1 meter | 1.0 meter | 39.37 inches |
| 1 kilometer | 1,000.0 meters | 0.62 miles |

And, about those temperature scales:

| | Absolute zero | Boiling point of water |
|---|---|---|
| Kelvin | 0° | 373° |
| Centigrade | −273.16° | 100° |
| Fahrenheit | −459.69° | 212° |

Several other terms in these articles set us thumbing through the dictionary. So that you may not have to do the same for all of them, here's a selected list:

maser—a device for amplifying electrical impulses by stimulated emission of radiation.
on-line—operating as part of or directly connected to the main computer.
radio occultation—the shutting off of light or radio waves of one celestial body by the intervention of another.
real time—the actual time elapsed in the performance of a computation by a computer, the result of the computation being required for a physical process.
seismogram—a record made by a seismograph.
seismograph—any of various instruments for measuring and recording the vibrations of earthquakes.
seismometer—a seismograph equipped for measuring the direction, intensity, and duration of earthquakes by measuring the actual movement of the ground.
shadow zone—a region between 103° (11,433 km) and 145° (16,096 km) from the focus of an earthquake. The size and clarity of the P motion shown on a seismogram depend on how far away from the recording station the epicenter of an earthquake is. As the distance increases, the onset of motion becomes less, until at about 103° it becomes decidedly indistinct. The movement becomes sharp again at about 145°. The region where the wave is indistinct is called the "shadow zone for P." The reason for it is that once the ray from an earthquake penetrates so deeply into the earth that it must pass through the core, it will be sharply bent and emerge at a greater distance than it otherwise would.
terminator—the dividing line between the illuminated and the unilluminated part of a planet or moon's disk.

**Sample Profile**

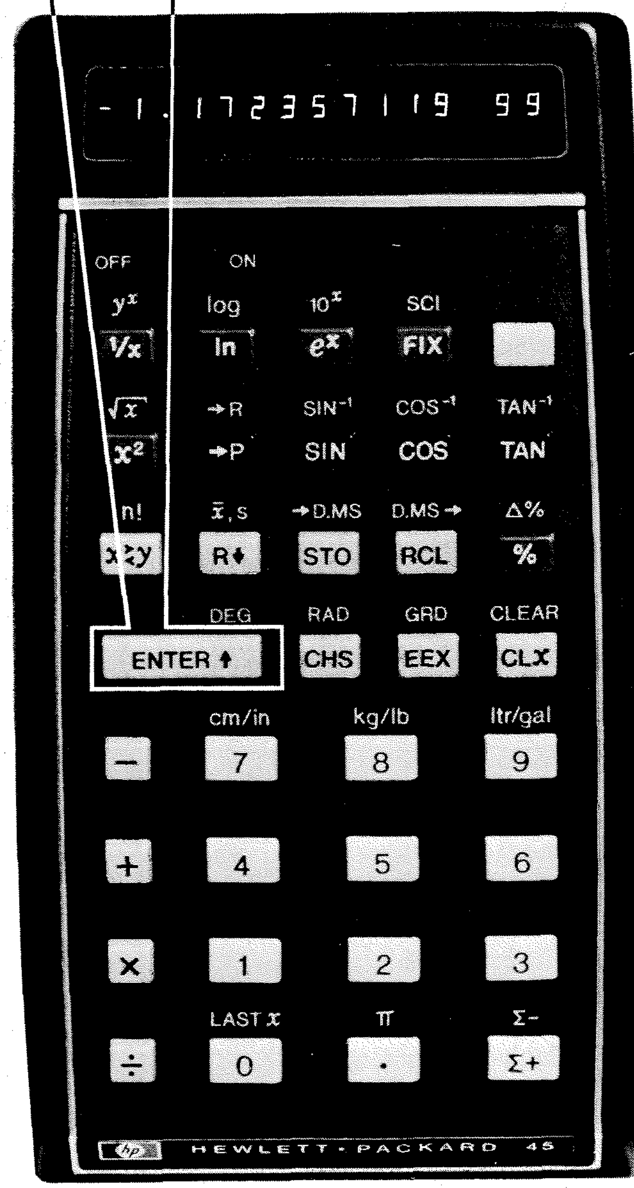
To refresh your memory about the structure and dimensions of the earth—if we could take a core sample straight through to the center, it would look, and measure, about like this:

The total length of the sample, the mean radius, would be about 6,370 km (3,950 miles). Of this, the outermost layer, the crust, would be about 10-50 km thick (6-30 miles).

The mantle is the next layer, and it is about 2,900 km thick (1,800 miles).

The inner layer is called the core, and its total depth is about 3,470 km (2,151 miles). But the core itself is divided into outer and inner layers. The thickness of the outer core is about 2,170 km (1,345 miles), leaving 1,300 km (806 miles) as the radius of the inner core.


# This is your key to unprecedented calculating power. Only Hewlett-Packard offers it.




In 1928 a Polish mathematician, Dr. Jan Lukasiewicz, invented a parenthesis-free but unambiguous language. As it's evolved over the years it's come to be known as Reverse Polish Notation (RPN), and it's become a standard language of computer science.

Today, it's the only language that allows you to "speak" with total consistency to a pocket-sized calculator. And the only pocket-sized calculators that use it are Hewlett-Packard's

[ENTER↑] is the key to RPN because it enables you to load data into a 4-Register Operational Stack with the following consequences:

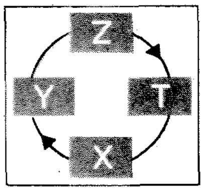
1. You can *always* enter data the same way, i.e. from left to right, the natural way to read any expression.
2. You can *always* proceed through your problem the same way. Once you've entered a number you ask: "Can I operate?" If yes, you perform the operation. If no, you press [ENTER↑] and key in the next number.
3. You can see *all* intermediate data anytime, so you can check the progress of your calculations *as you go.*
4. You almost never have to re-enter intermediate answers—a real time-saver, especially when your data have eight or nine digits each.
5. You don't have to think your problem all the way through beforehand to determine the best method of approach.
6. You can easily recover from errors since each operation is performed sequentially, immediately after pressing the appropriate key, and all data stored in the calculator can be easily reviewed.
7. You can communicate with your calculator efficiently, consistently and without ambiguity. You always proceed one way, no matter what the problem.

# The HP-45 uses RPN.

That's one reason it's the most powerful pre-programmed pocket-sized scientific calculator. Here are 8 others:

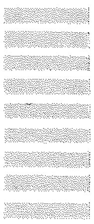
**1.** It's pre-programmed to handle 44 arithmetic, trigonometric and logarithmic functions and data manipulation operations beyond the basic four (+, −, ×, ÷).

**2.**




It offers a 4-Register Operational Stack that saves intermediate answers and automatically retrieves them when they are required in the calculation.

**3.**



It lets you store up to nine separate constants in its nine Addressable Memory Registers.

**4.** It gives you a "Last X" Register for error correction or multiple operations on the same number. If you get stuck midway through a problem, you can use the "Last X" Register to unravel what you've done.

**5.** SCI / FIX It displays up to 10 significant digits in either fixed-decimal or scientific notation and automatically positions the decimal point throughout its 200-decade range.

**6.** →D.MS STO D.MS→ RCL It converts angles from decimal degrees, radians or grads to degrees/minutes/seconds and back again.

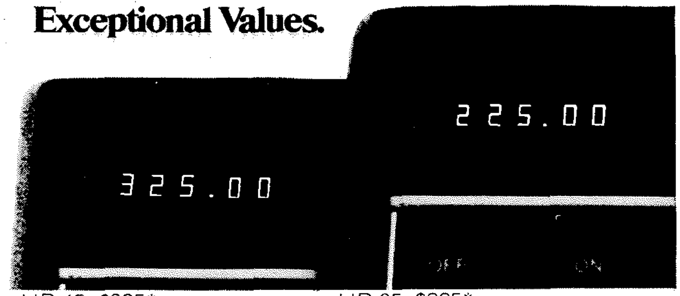
**7.** →R / →P It converts polar coordinates to rectangular coordinates . . . or vice-versa. In seconds.

**8.** Its Gold "Shift" Key doubles the functions of 24 keys which increases the HP-45's capability without increasing its size.

# The HP-35 uses RPN too.

If the HP-45 is the world's most powerful pre-programmed pocket-sized scientific calculator, the HP-35 is runner-up. It handles 22 functions, has a 4-Register Stack, one Addressable Memory Register and also displays up to 10 digits in either fixed-decimal or scientific notation.

## Exceptional Values.




HP-45: $325* HP-35: $225*

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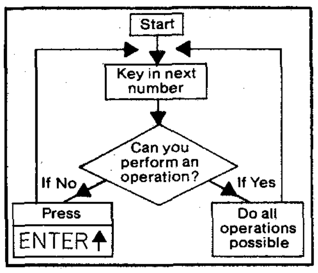


It demonstrates the superiority of Dr. Lukasiewicz' language by comparing it to other calculators' systems on a problem-by-problem basis, and it explains the algorithm shown to the left which lets you evaluate any expression on a calculator that uses RPN and an Operational Stack. This booklet is must reading for anyone seriously interested in owning a powerful pocket-sized calculator.

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# Development and Design. Is this the kind of engineering for you?

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General Electric employs quite a few engineers. So we thought a series of ads explaining the work they do might come in handy. After all, it's better to understand the various job functions before a job interview than waste your interview time trying to learn about them.

Basically, engineering at GE (and many other companies) can be divided into three areas. Developing and designing products and systems. Manufacturing products. Selling and servicing products.

This ad outlines the types of work found in the Development and Design area at GE. Other ads in this series will cover the two remaining areas.

We also have a handy guide that explains all three areas. For a free copy, just write: General Electric, Educational Communications, W1D, Fairfield, CT 06431.

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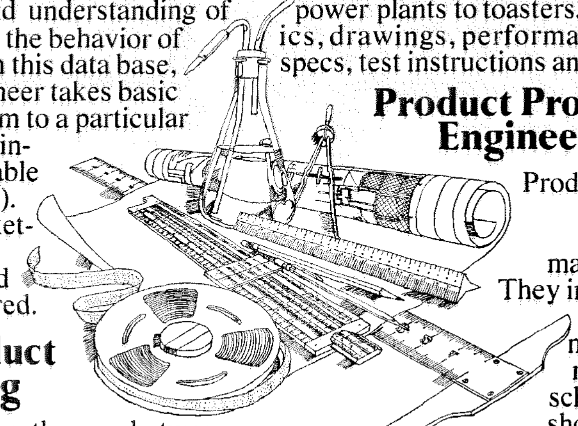

## Advance Product Engineering

Advance engineers bridge the gap between science and application. Their job is to understand the latest advances in materials, processes, etc., in a product area, then use this knowledge to think up ideas for new or improved products or to solve technical problems. They must also prove the technical feasibility of their ideas through laboratory testing and models. Requires a highly creative, analytical mind. A pioneering spirit. And a high level of technical expertise. Output is often a functional model.

## Product Design Engineering

Design engineers at GE pick up where the advance engineer leaves off. They take the product idea and transform it into a product design that meets given specs and can be manufactured. Usually, they are responsible for taking their designs through initial production to prove they can be manufactured within cost. Requires a generalist who can work with many experts, then put all the pieces together to make a product. From power plants to toasters. Output is schematics, drawings, performance and materials specs, test instructions and results, etc.

## Product Production Engineering

Production engineers interface between the design engineer and manufacturing people. They interpret the product design intent to manufacturing. They maintain production scheduling by troubleshooting during manufacturing and determining deviations from specs. When necessary, they help design adaptations of the product design to improve quality or lower cost without changing the essential product features. Requires intimate familiarity with production facilities.

## Engineering Management

For people interested in both engineering work and management. Engineering managers plan and coordinate the work of other engineers. They might oversee product development, design, production, testing or other functions in marketing and manufacturing. Requires a strong technical base gained through successful engineering work. Sensitivity to business factors such as cost and efficiency. Plus the ability to work with people.

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