E&S

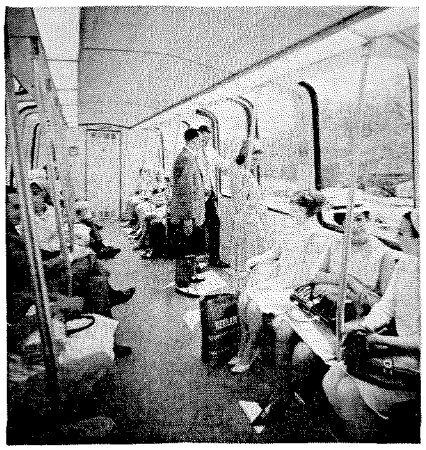
ENGINEERING AND SCIENCE

PUBLISHED AT THE CALIFORNIA INSTITUTE OF TECHNOLOGY

November 1967

Jobs that just might change the world

Move people through rush hours at 80 mph. Westinghouse built the experimental transit expressway in Pittsburgh. And we are building the computerized controls for the San Francisco mass-transit system that will be the model for others throughout America. We're looking for people to help us build equipment that will move people as they've never been moved before.



These graduates needed: Engineering, Physical Sciences, Social Sciences, Engineering Administration, Industrial Technology, Business & Liberal Arts.

Tap the atom with the company that started it all. Westinghouse supplies some of the largest nuclear generating plants in the world. We are building nuclear rocket engines. Our reactors power nuclear submarines. But this is only the start. We need people for some of the most fascinating projects we've ever attempted.

These graduates needed: Electrical Engineering, Mechanical Engineering, Industrial Engineering, Chemical Engineering, Engineering Mechanics, Marine Engineering, Structural Engineering, Ceramics, Nuclear Engineering, Materials Science, Physical Sciences.

Desalt the world's oceans

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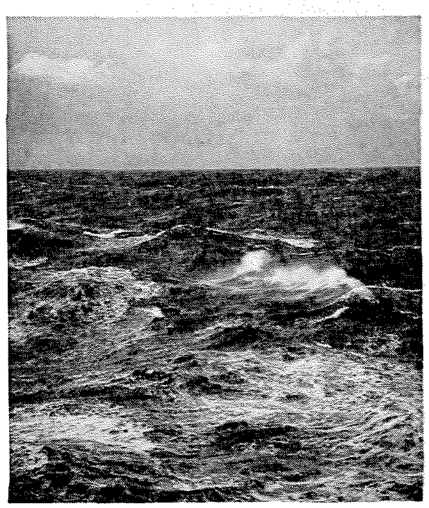
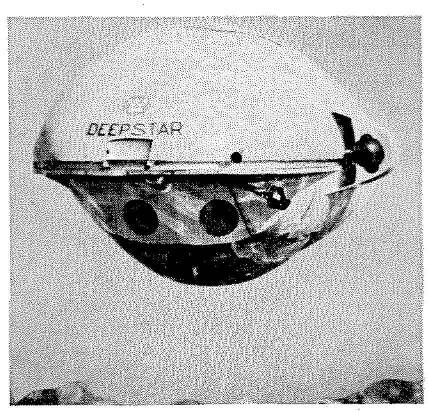


These graduates needed: Electrical Engineering, Chemical Engineering, Materials Science, Physical Sciences, Industrial Engineering, Engineering Mechanics, Mechanical Engineering, Civil Engineering.

Take a dive and explore the ocean 20,000 feet down. Westinghouse is developing a fleet of self-propelled undersea vehicles. In them we will dive deep, explore, salvage and probably discover more than any other single company in oceanography. We need adventurers to join the quest that has already taken us all over the world.



These graduates needed: Electrical Engineering, Mechanical Engineering, Chemical Engineering, Materials Science, Marine Engineering, Ocean Engineering & Science.

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These graduates needed: Engineering, Physical Sciences, Social Sciences, Engineering Administration, Industrial Technology, Business & Liberal Arts.

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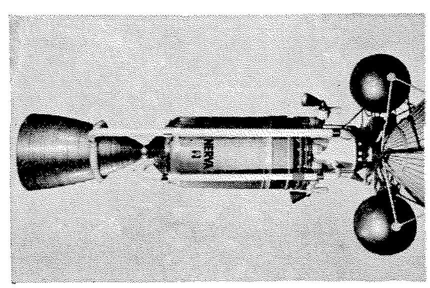
When the first expeditionary vehicle takes off, Westinghouse will be there.

We are building the nuclear engine for voyages into deep space—to Mars and Venus and beyond. The jobs are exotic. We need more people to help us now.



These graduates needed: Electrical Engineering, Mechanical Engineering, Chemical Engineering, Materials Science, Nuclear Engineering, Aerospace Engineering, Physical Sciences.

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And that can be an advantage.

How? Well, take Ford Motor Company. We're a giant in an exciting and vital business. We tackle big problems. Needing big solutions. Better ideas. And that's where you come in. Because it all adds up to a real opportunity for young engineering graduates like yourself at Ford Motor Company.

Come to work for us and you'll be a member of a select College Graduate Program. As a member of this program, you won't be just another "trainee" playing around with "make work" assignments.

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A network of computers to put confusing facts and figures into perspective.

Complete testing facilities to prove out better ideas.

And at Ford Motor Company, your better ideas won't get axed because of a lack of funds. (A giant doesn't carry a midget's wallet, you know.)

Special programs. Diverse meaningful assignments. Full responsibility. The opportunity to follow through. The best facilities. The funds to do a job right. No wonder 87% of the engineers who start with Ford are here 10 years later.

If you're an engineer with better ideas, and you'd like to do your engineering with the top men in the field, see the man from Ford when he visits your campus. Or send your resume to Ford Motor Company, College Recruiting Department.

You and Ford can grow bigger together.

Ford

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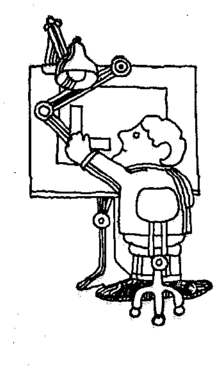
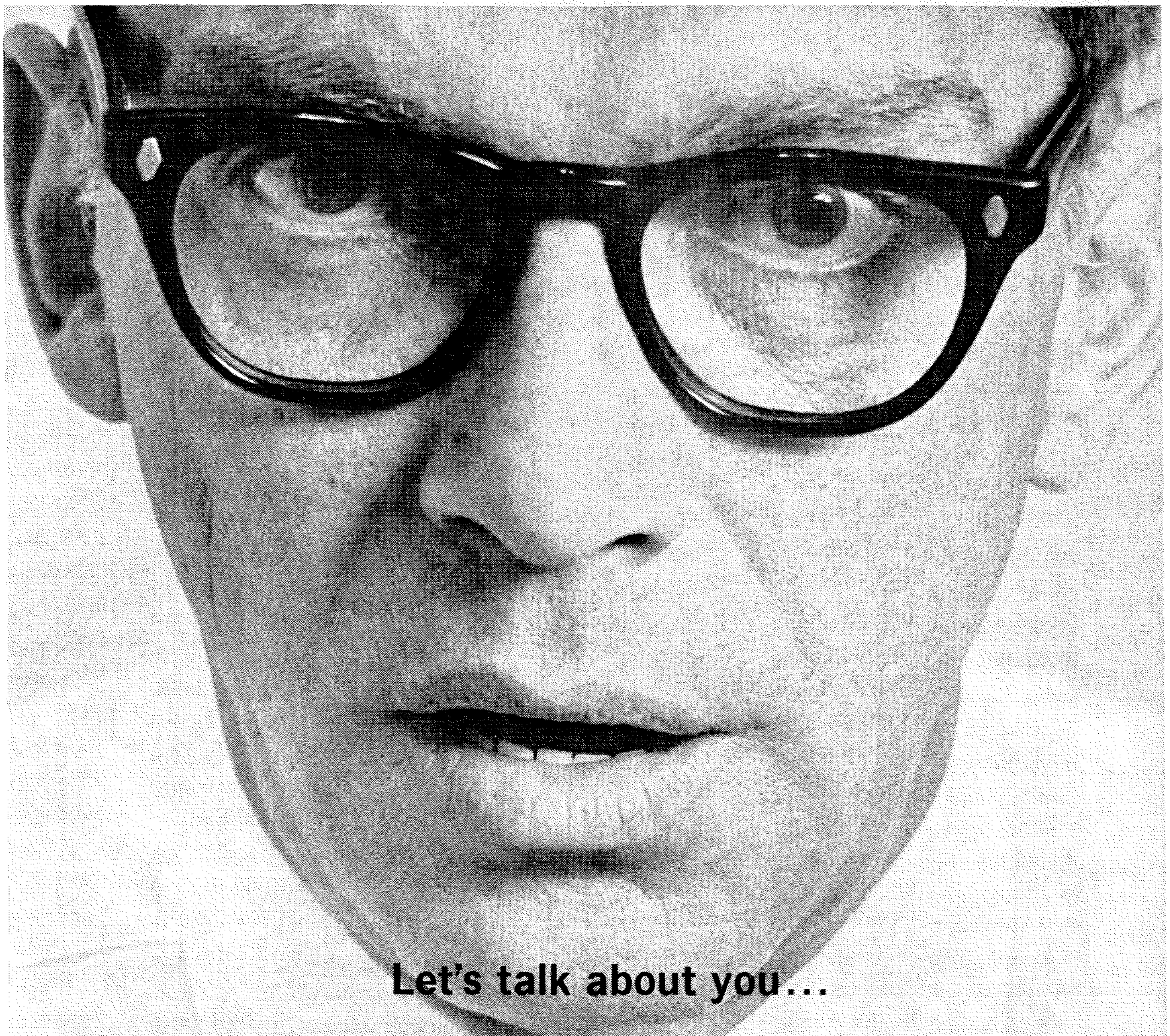
AN EQUAL OPPORTUNITY EMPLOYER.

What's it like to engineer for a giant?

Rather enlarging!





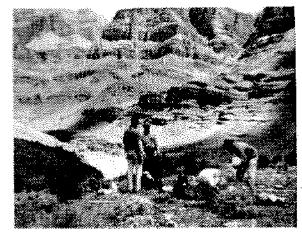
E&S

ENGINEERING AND SCIENCE

NOVEMBER 1967 / VOLUME XXXI / NUMBER 2

A SPECIAL ISSUE ON GEOLOGY AT CALTECH

ON THE COVER



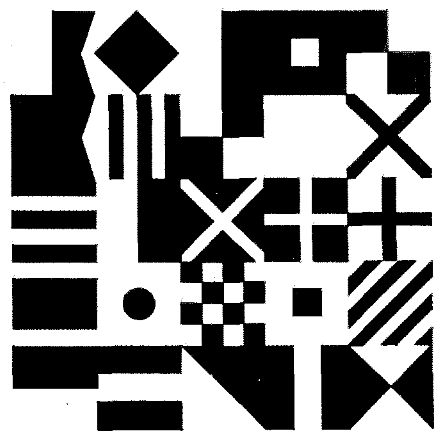
A team of Caltech staff geologists and students at the foot of the old Bass Trail in the Inner Gorge of the Grand Canyon. The group is collecting samples of the oldest rocks in the Canyon, stacking them up at a helicopter pickup site to be taken back to the Caltech geology laboratories, where isotopic studies will reveal the age and origin of the material. This combination of field study and laboratory analysis is typical of much of the work in geology at Caltech today—and therefore a fitting introduction to this special geology issue of *Engineering and Science.*

PICTURE CREDITS

Cover—Douglas Smith
10,13,15,36—Clarence Allen/14—V. Solonenko/ 17—Mt. Wilson and Palomar Observatories / 18—Jet Propulsion Laboratory / 29,31-33—Barclay Kamb and Edward R. LaChapelle / 5,39,47 —Jim McClanahan / 56,61—Ewing Galloway / 59,62—Al Greene & Associates / 63—American Stock Photos.

What is there left for you to discover?

Cyrus the Great, King of Persia, built a communications system across his empire some six centuries before the Christian Era. On each of a series of towers he posted a strong-voiced man with a megaphone. By the 17th century, even a giant megaphone built for England's King Charles II could project a man's voice no further than two miles. Charles II richly rewarded Admiral William Penn, father of the colonial Quaker, for developing a fast, comprehensive communications system — ship-to-ship by signal flags.



We waited for the combined theories of Maxwell, Hertz, Marconi and Morse before men could transmit their thoughts by wireless, though only in code. Only after Bell patented his telephone and DeForest designed his audion tube could men actually talk with each other long-distance. Today nations speak face-to-face via satellite. Laser-beam transmission is just around the corner. Yet man still needs better ways to communicate across international boundaries.

In a world that has conquered distance, in a world whose destiny could hinge on seconds, man is totally dependent on the means which carry his voice and thought. It is this means that we in Western Electric, indeed the entire Bell System, have worked on together since 1882.

Our specialty at Western Electric is the manufacture and installation of dependable, low-cost communications systems for both today and tomorrow. And to meet tomorrow's needs, we will need fresh new ideas. Your ideas. There is still much for you to discover right here at Western Electric.

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Western Electric
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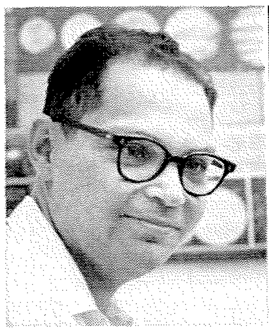
Allen

Goldstein

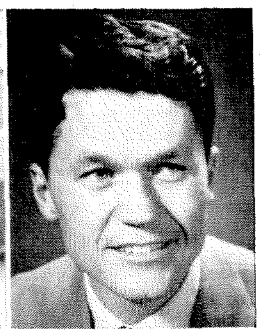
THIS ISSUE

of *Engineering and Science* magazine is a special report on the nature and scope of geology at Caltech today. The 11 articles in the issue have all been contributed by members of the faculty in the Division of Geological Sciences. The articles and the work they describe are representative of the broad spectrum of research and study in the field of geology at the Institute in 1967.

Sharp



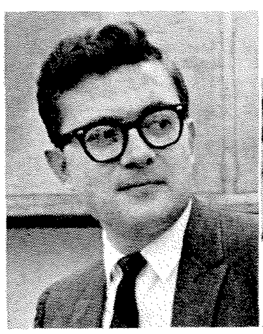
Burnett



Kamb

Brune

Albee



Anderson

Epstein

Lowenstam

Richter

Robert P. Sharp, professor of geology and chairman of the division, on leave, contributes an introduction to this special issue (page 9) and an article on the science of land forms, "Geomorphology in the Space Age" (pages 61-63).

Clarence R. Allen, professor of geology and geophysics and interim director of Caltech's Seismological Laboratory for the past two years, is now acting chairman of the geology division. His "Earthquakes, Faulting, and Nuclear Reactors" is on pages 10-16.

Richard M. Goldstein is manager of the telecommunications research section at Caltech's Jet Propulsion Laboratory and visiting associate professor of planetary science at the Institute. He writes about "The Mountains of Venus" on pages 17-20.

Donald S. Burnett, assistant professor of nuclear geochemistry, tells how the study of "Nuclear Processess in Meteorites" (pages 21-23) can lead to a nuclear history of the solar system.

Barclay Kamb, professor of geology and geophysics, is engaged in the investigation of rock deformation and glacier flow. From these studies comes his article on pages 27-33, "Ice Under Stress and Pressure, Ice in Order and Disorder."

James Brune, associate professor of geophysics, in "The Fault Slips" (pages 36-38), describes the processes which are deforming California along the San Andreas Fault and relates the number of earthquakes and the rate of slip along the fault.

Arden L. Albee, professor of geology, writes about the use of the electron microprobe x-ray analyzer in petrologic and mineralogic investigation in "Rocks—Micron by Micron" on pages 39-42.

Don L. Anderson, associate professor of geophysics and director of Caltech's Seismological Laboratory, in "The Mantle of the Earth" (pages 43-46), describes the efforts to build up an adequate description of the earth's interior.

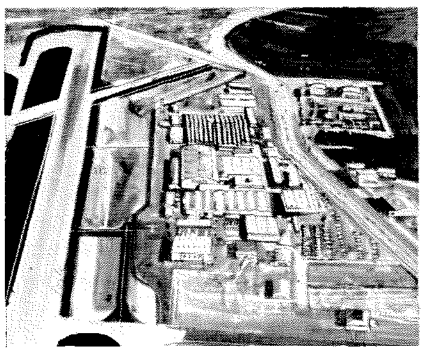
Samuel Epstein, professor of geochemistry, writes about "The Stable Isotopes" on pages 47-51, which, in part, describes his studies of the variations of oxygen and carbon isotopes in nature.

Heinz A. Lowenstam, professor of paleoecology, conducts ecological studies of recent and fossil marine organisms. His article "Fossil Sensors" is on pages 52-55.

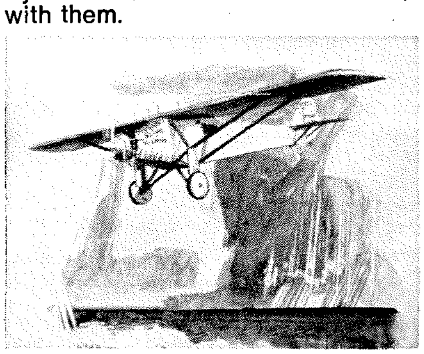
Charles Richter, professor of seismology, is concerned with the magnitude, statistics, and geography of earthquakes. His article "California Earthquakes" on pages 56-60 presents his observations about both historic and recent earthquakes in the state.

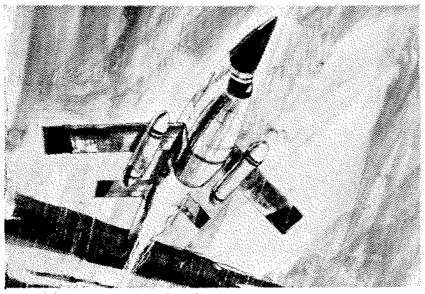
Here's what we mean when we say, "Ryan is a better place to work."

We mean that a pioneer aerospace company still headed by the man who founded it 45 years ago has *got* to be a company that cares about its people. T. Claude Ryan, founder and chairman, is still at the office every day. To him, Ryan employees are friends. Old ones and new ones alike. Ryan headquarters, combining engineering and manufacturing facilities, are on the shores of San Diego bay, where it all started in 1922.

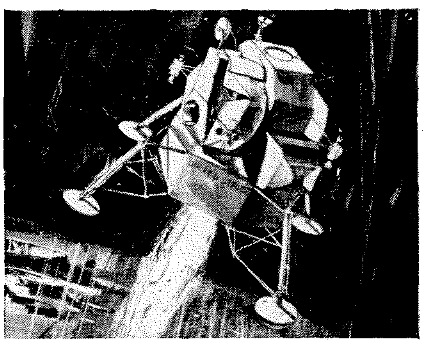


We mean that a company so rooted in aviation history is bound to be a leader in vitally important defense/space programs. The outgrowth of the original Ryan Airlines, Inc., that built the "Spirit of St. Louis" in 60 days from a standing start will always be ready to accept impossible challenges. And ready to listen to young men of vision who can dream up answers to those challenges. Ideas are given a chance at Ryan. So are the men who come up with them.

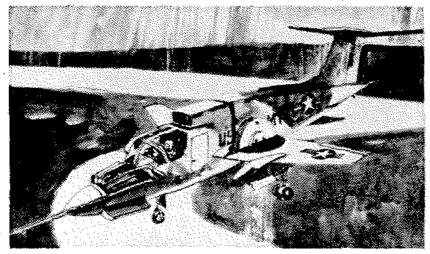




We mean that a company which led the world in the conception and development of jet-powered target drones is the kind of company where daring and untried ideas come to life. Over 3,000 Ryan Firebees, the most versatile aerial targets ever conceived, are in use with all three branches of our armed forces, helping to train our defenses against any airborne threat. A super-sophisticated, supersonic Firebee II will soon be flight tested and enter service.



We mean that a company whose heart has always been in the wild blue yonder would just naturally be there when man reached for the stars; that the products of its scientists, engineers and technicians would naturally play a key role in our race for space. Ryan landing radar systems made possible the first soft landing on the moon. And an advanced Ryan system will assure a soft landing for the first manned lunar visit. The men at Ryan already have their eyes on the space beyond the moon.



We mean that a company made up of men who taught themselves to fly straight up, while others said it couldn't be done, is the sort of place that puts no strings on a man's imagination. Or barriers in the way of way-out thinking. For over twenty years Ryan has been amassing an unmatched fund of technology in vertical and short take off and landing (V/STOL) aircraft. The list of accomplishments is long: Dragonfly, 1940. Vertijet, 1957. Vertiplane, 1959. The present day XC-142A tilt-wing and the XV-5A Vertifan. Ryan products can fly straight up. So can the men who work there.

We mean that a company with a strong and capable management—whose business success has led to majority ownership of large related companies — is the kind of concern that can match challenges with permanent opportunities. Ryan Aeronautical is majority owner of Continental Motors Corporation and its subsidiaries, suppliers of primary power for both piston and jet aircraft and agricultural, military, marine and industrial equipment. There is nothing provincial about Ryan. Including subsidiaries, it operates 16 manufacturing facilities in the USA and Canada.

We mean, also, that *San Diego* is a better place to work—because it's a better place to *live*. It's the surfing, sailing, deep-sea fishing and golfing capital of the country. It's clean, uncrowded and friendly and you can lead the good life year 'round. Its great universities make education one of its largest industries. Ryan is an important and respected member of this dynamic community . . . a community on the move.

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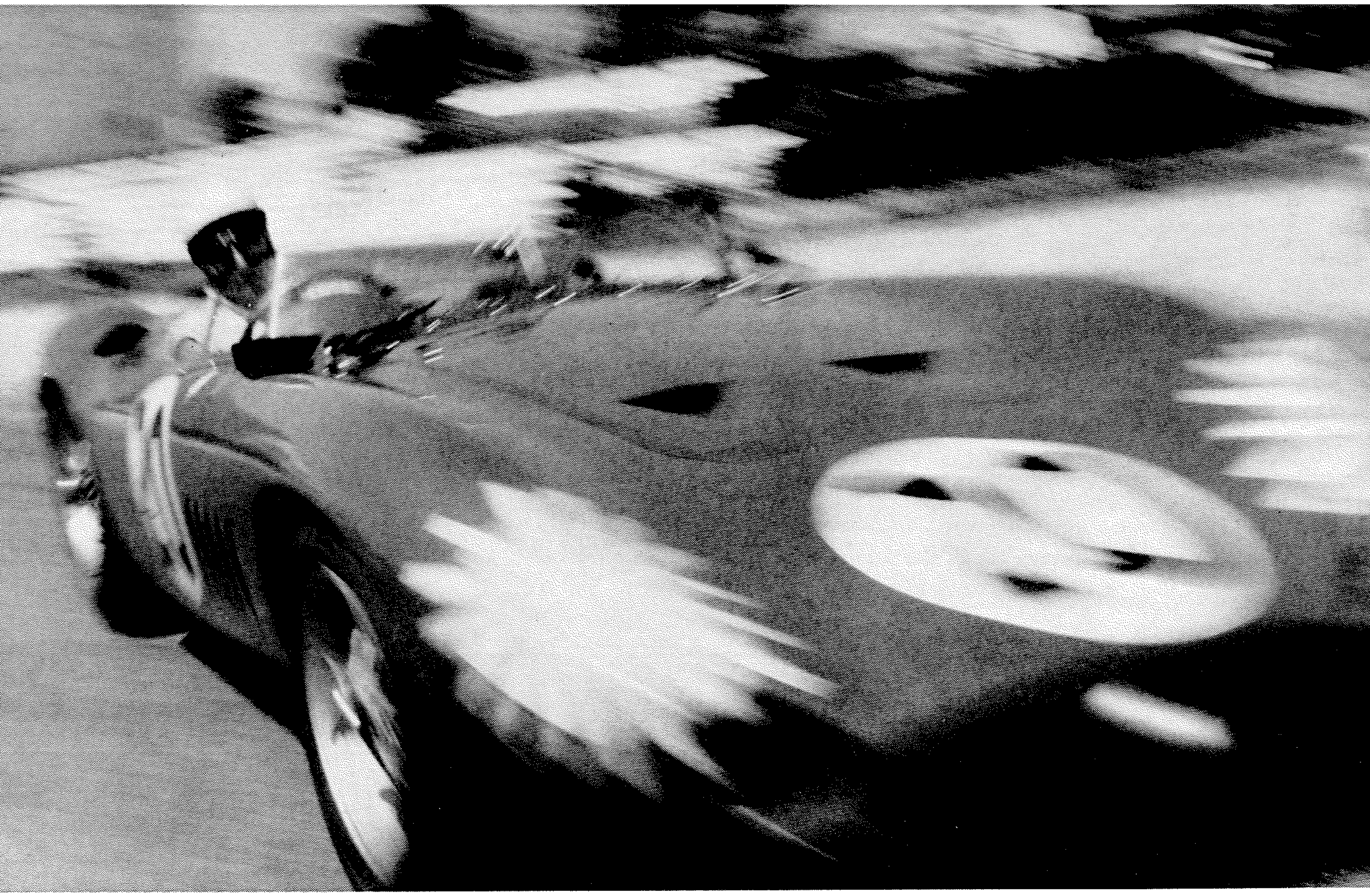
This is what we mean when we say, "Ryan is a better place to work." The 4,500 men and women now at Ryan know it is. And they invite your inquiry. Check with your placement office for our campus visit, or write to Mr. Harlow McGeath, Ryan Aeronautical Company, Lindbergh Field, San Diego, Calif. 92112.



Can there be this kind of excitement in engineering?

A high-performance car in a four-wheel drift around the first turn at Watkins Glen* typifies the excitement of sportscar racing... precision machinery and human skill in cool coordination.

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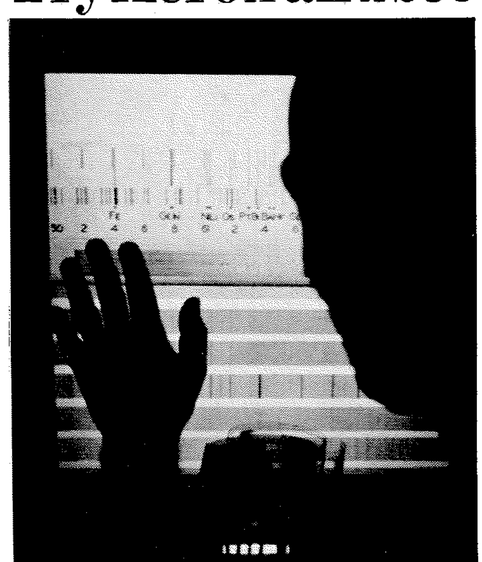

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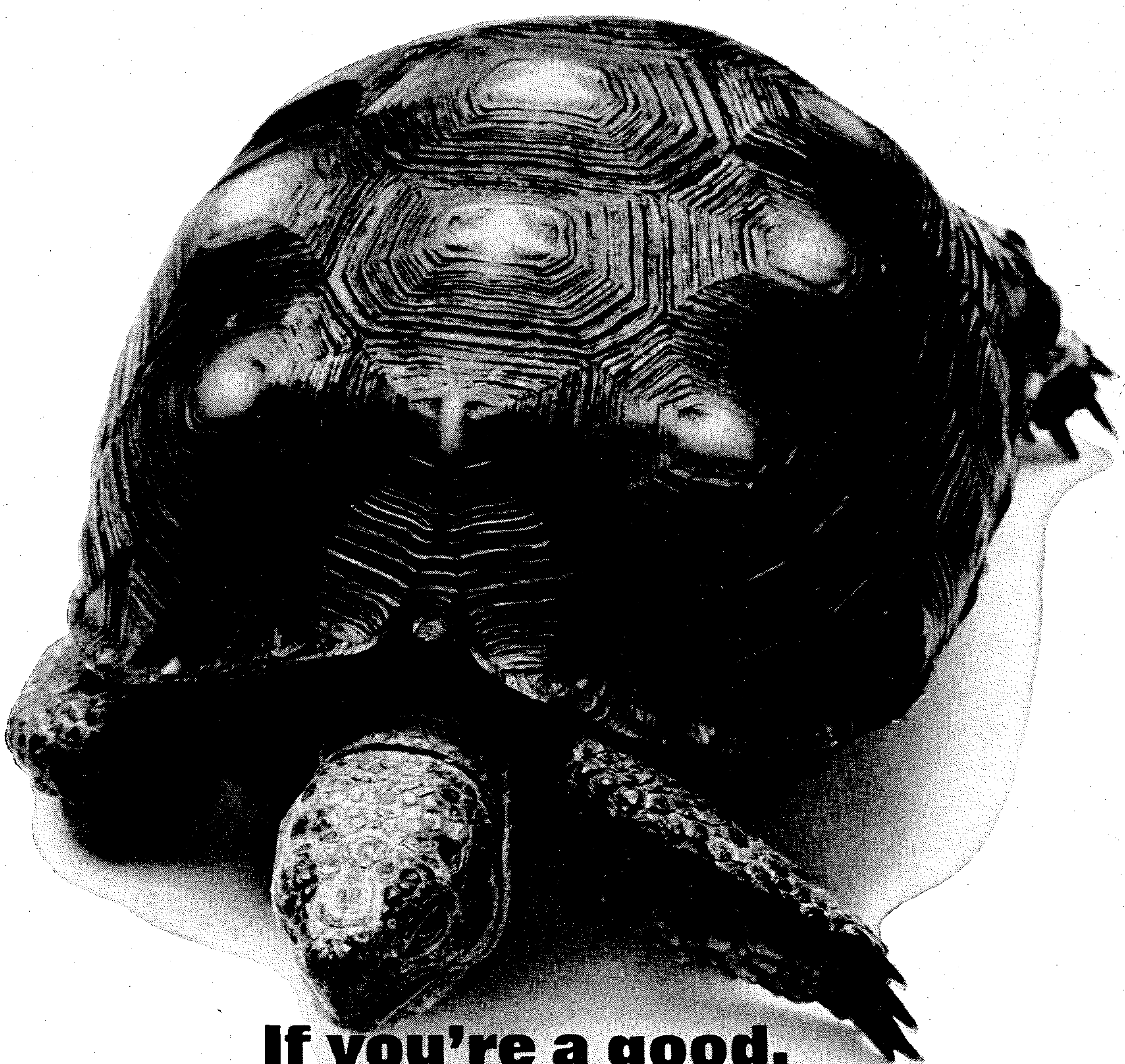


A Special Issue of Engineering and Science Devoted to

GEOLOGY AT CALTECH

Nearly 20 years ago *Engineering and Science* (February 1948) published an issue devoted solely to articles by the staff of the Caltech geology division. Those 11 articles by 9 authors provided a representative cross section of interests and activities within the geology division in the late 1940's. The issue in hand, comprising 12-13 articles, presents a sampling of divisional interests in the late 1960's. These two issues of *Engineering and Science* constitute an interesting historical record of evolution in geological activities over two decades. Even to those involved, the changes in personnel and orientation have been surprisingly great. Professional appointments of all ranks numbered 14 in 1948 and 23 in 1967. Of the nine authors contributing to *E&S* in 1948, only two (Charles Richter and Robert Sharp) are on the staff now. John Buwalda, Beno Gutenberg, and Chester Stock are deceased; Hugo Benioff and James Noble are retired; Richard Jahns is a dean at Stanford; and Ian Campbell is director of the State of California Division of Mines and Geology.

The articles of 1948 focused on gems, fossils, ore minerals, faulting, earthquakes, the earth's interior, rock study, seismometers, and surface features. Some of these same topics are treated in the current edition, but in addition there are articles on meteorites, geochemistry, geochronology, the microprobe, and planetary science.

Geology at Caltech has undergone much change in the last two decades. Since 1948, a major operation in geochemistry has been initiated and now permeates all parts of the division. Seismology remains a major endeavor, just as it was in 1948, but geophysics is being broadened and strengthened. Recently, major efforts have gone to build a staff, research competence, and a graduate student program in planetary science. The division has become a user of sophisticated laboratory procedures and complex pieces of apparatus such as mass spectrometers, an electron microprobe, and an infrared telescope. Some of the finest chemical laboratories on campus, and by necessity probably the cleanest, are in the geology division. The horizons and scope of geology have so broadened that at times the name hardly seems inclusive enough. Geologists, geochemists, and geophysicists are now joining divisional planetary scientists in probing the origin, composition, and history of the moon and other planets.

In spite of all this, a common basis of geology or earth science underlies the activities of the division, integrating them into a meaningful whole. We still practice field geology and insist on extensive student training therein. The Caltech field training program extending through the junior and senior years and involving part of the intervening summer is probably one of the most thorough in North America. Some of the staff remain primarily field men, and many others rely upon field work to define problems, provide materials for laboratory analyses, and test theories and hypotheses.

Work in other classical geological subjects is still carried on, in different ways to be sure, but the objective is the same—namely, to learn all we can about the earth, its origin, constitution, and evolutionary history, as well as its current and future behavior.

The scope is now being broadened to include the moon and other planets. Field work in these environments is not yet possible, but the earth scientist who has done his field work on earth and his homework in the fundamental aspects of geology, geochemistry, and geophysics is going to be in a position to contribute significantly to the rapid developments in planetary exploration coming up over the horizon.

Any educational and research organization that remains unchanged is dead. This issue of *Engineering and Science* provides testimony to the continuing viability of the Caltech geology division. It will be interesting to see what another issue looks like 20 years hence.

—ROBERT P. SHARP
professor of geology and chairman of the Division of Geological Sciences (on leave)

Airview shows the trace of the San Andreas fault in Carrizo Plain, west of Bakersfield, California. The elongate scarp in the foreground and the linear break in the field beyond show the line of displacement during the great 1857 earthquake, which followed the same path as previous breaks in the recent geologic past.

EARTHQUAKES, FAULTING, AND NUCLEAR REACTORS

by Clarence R. Allen

Most of the recent controversy concerning seismic hazards to proposed nuclear facilities in California has centered not on the usual problems of earthquake-resistant design but instead on the possible hazards associated with ground displacements by faulting through the foundation of a nuclear plant. In addition, there has been much difference of opinion as to the maximum credible earthquake that should be specified for any given area.

A large proportion of the public opposition to specific sites has centered on the problem of safety, because many individuals have apparently felt—rightly or wrongly—that this was the only effective political means by which they could oppose the development. The government has made it very clear that exceptionally stringent safety requirements must be satisfied before plants will be licensed. Within the field of safety, arguments have tended to focus on geological aspects of the seismic hazard, partly because this field is admittedly less quantitative and less thoroughly understood than engineering aspects, and thus more open to debate.

Nevertheless, some very legitimate geological-seismological questions have been raised in these controversies, and some proponents of specific sites have tended to underestimate these factors in the over-all evaluation of safety. Furthermore, it has become abundantly clear that more research is needed in this field if we are to be fully confident that our seismic design and siting criteria are adequate to ensure public safety.

Much evidence has accumulated in recent years to indicate that most earthquakes are caused by faulting. During large earthquakes this faulting may start at some depth in the earth's crust and extend to the surface where it abruptly displaces the ground by as much as 11 meters vertically (India, 1897) and 9 meters horizontally (Mongolia, 1957). Even very small earthquakes are occasionally accompanied by surface faulting if the focus is unusually shallow; a recent shock of magnitude 3.6 in the Imperial Valley of California, where it was only locally felt, was associated with a 1.5-cm horizontal displacement at the surface along the Imperial fault.

Continuous gradual slippage (or "creep") along

"Earthquakes, Faulting, and Nuclear Reactors" has been adapted from a talk given to the International Association of Atomic Energy panel meeting on Aseismic Design and Testing of Nuclear Facilities in Tokyo, June 1967.

Gradual horizontal slippage, or "creep," has been taking place for several years along a branch of the San Andreas fault in Hollister, distorting this wall and damaging a number of houses along the fault trace.

faults, without accompanying earthquakes, is being observed at an increasing number of localities in California. It now appears that this is a much more common phenomenon than we thought only a few years ago. Slippage along the San Andreas fault near Hollister averages about 1.7 cm/yr, and slippage along the same fault near Parkfield continues at about 0.1 mm/day even one year after the magnitude 5.6 earthquake that started this particular "episode."

Slippage may well have occurred episodically along virtually all active faults in California, and this is an additional reason for avoiding such faults in locating major engineering structures—a reason that is not being fully appreciated in numerous current housing developments in California. Particularly in the San Francisco and San Bernardino areas, many houses have recently been built squarely astride the most recent trace of the San Andreas fault in areas where it could have and should have been clearly recognized and taken into consideration.

Vertical aerial photograph of the northern part of San Bernardino, taken in the late 1920's. The dark line crossing the picture delineates the most active trace of the San Andreas fault, which dams ground-water and thus controls vegetation. This line is barely visible on more recent photographs because much of the area is now covered by houses—many of them straddling the fault trace.

The white line along this mountain front is the 1915 earthquake scarp south of Winnemuca, Nevada. Despite the predominance of vertical displacement, the scarp is a single, relatively simple break along most of its 35-km length.

Although small earthquakes occur in nearly all parts of California, almost all large earthquakes have occurred in close association with major faults that had been or could have been mapped by geologists prior to the earthquakes. Likewise, future large earthquakes will probably be limited to areas of active faulting, and most active faults in this region can be recognized by physiographic features of the disturbed ground surface, such as recent scarps, elongate closed depressions, rift-like valleys, and displaced stream channels.

Indeed, the geologist is generally in a better position to delineate these areas of possible large earthquakes than is the seismologist, who must necessarily work with a relatively short history of instrumental records. Despite a very complete 34-year instrumental record of detailed seismicity in southern California by the Caltech Seismological Laboratory, there are many reasons for believing that this record is not a statistically adequate sample for extrapolating into the future. In fact, a seismic energy-release map for the past 34 years probably gives a partially *reversed* picture for the next 34 years, and extreme caution must be used in extrapolating historic seismicity data into the future unless many hundreds of years of data are available.

Similarly, a recent Caltech study of micro-earthquakes at more than 60 sites along the San Andreas fault system indicates that micro-earthquakes share the same statistical distribution as the larger shocks and are probably no better indicators of future activity. Parts of the San Andreas fault that have broken during great earthquakes as recently as 1857 and are prime candidates for future great earthquakes, nevertheless show a virtual absence of micro-earthquakes today. Segments of active faults characterized by occasional very large earthquakes may, in the intervening periods, be characterized by extremely low seismicity, possibly due to some "locking mechanism;" segments of faults characterized by the absence of very large earthquakes may, in turn, be characterized by more-or-less continuous seismic activity on a smaller scale. In any given area it will take the close cooperation of geologists and seismologists to give the best evaluation of potential seismicity, and engineers must recognize that a precise evaluation is an impossibility at the present state of the science.

Although California's San Andreas fault and associated earthquakes were once thought to be unique and unusual, recent studies indicate that the geological and seismological characteristics of California are shared by many other circum-Pacific areas. Regional throughgoing faults similar to the San Andreas have now been recognized in Alaska, Canada, Mexico, Venezuela, Chile, New Zealand, Sumatra, the Philippines, and Taiwan, in addition to far-removed areas such as Turkey. Nevertheless, not all areas of high seismicity appear to be tectonically dominated by similar throughgoing fault systems; Japan, for example, appears to be geologically very different from California, and it is important that we try to understand the reasons for these differences.

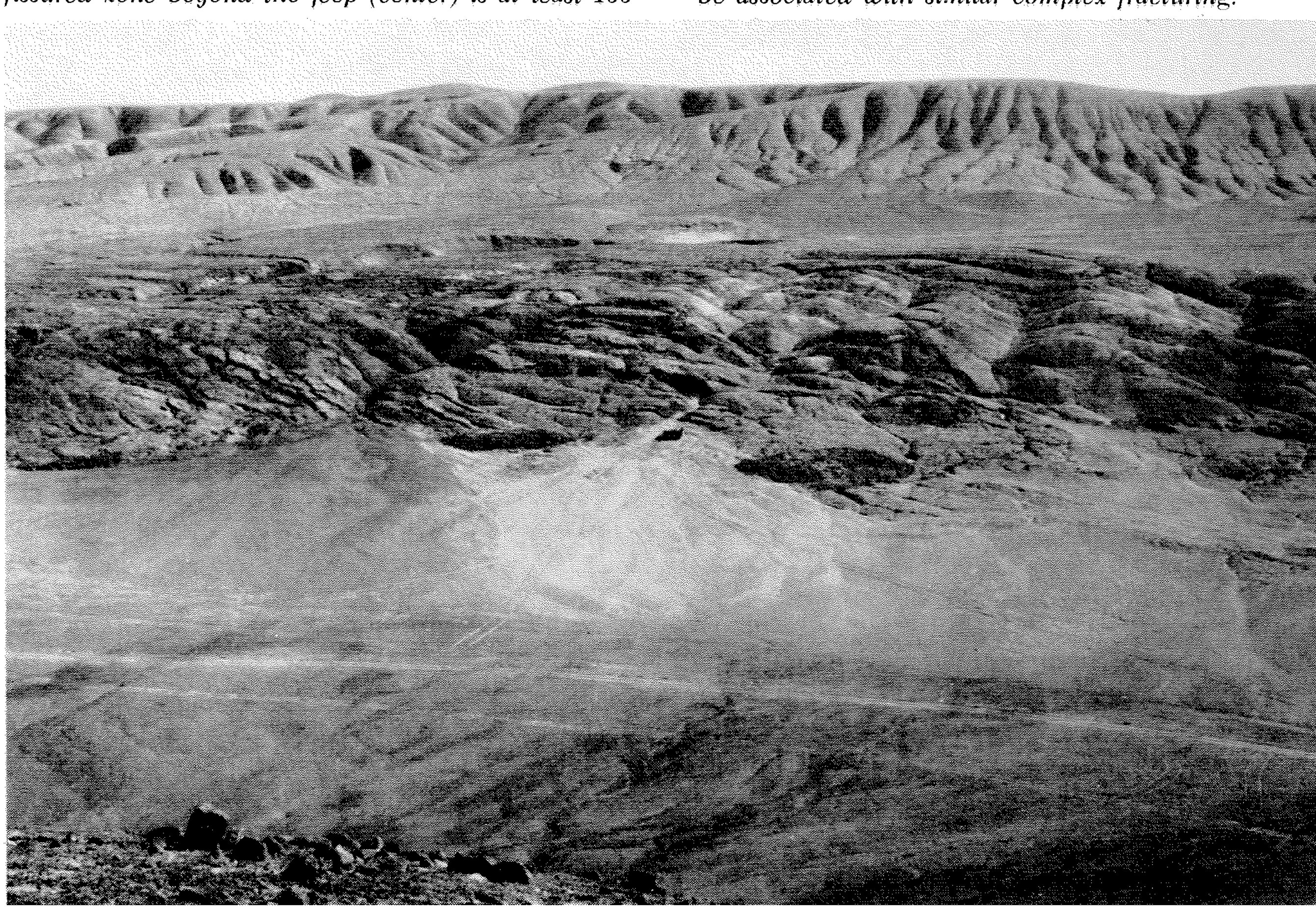
In California and many other parts of the world the largest earthquakes have been associated with the longest faults. Thus, the length and continuity of nearby faults have been major considerations in attempting to specify the maximum credible earthquake for a given locality. This generalization appears to be particularly valid for strike-slip faults (those with a history of horizontal rather than vertical displacements) as are common throughout most of California. Despite the many geological problems in trying to apply this type of criterion for establishing the maximum credible earthquake, it certainly has more justification in most areas than merely assuming that the largest nearby earthquake in the historic past is representative of the largest possible event in the future.

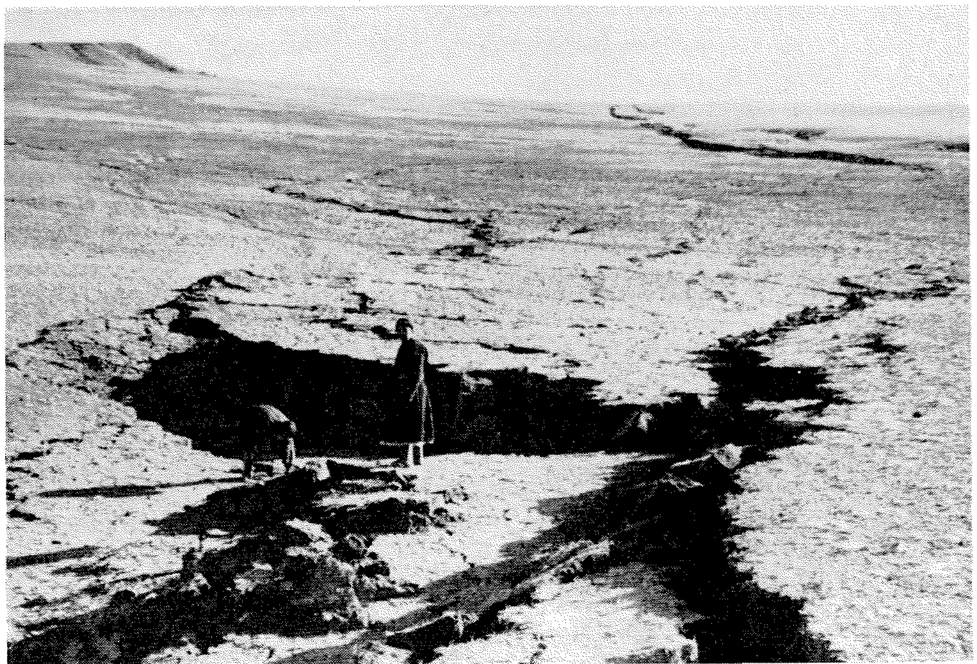
In the case of nuclear reactors, the specification of the maximum credible earthquake for which public safety must be assured demands extreme conservatism for two principal reasons: (1) the consequences of some types of serious failure in a nuclear facility must be guarded against even if their likelihood is exceedingly remote; and (2) the historic record of earthquake occurrences is so short that it cannot encompass the entire spectrum of possible events.

Almost every large earthquake that has occurred in California has proved to be surprising in terms of what would have been expected by geologists, seismologists, and engineers at the time. The recent unexpected events associated with the relatively small 1966 Parkfield-Cholame earthquake emphasize once again how little we know about what constitutes an "average"or "likely" earthquake. For this reason the present state of knowledge demands an unusually conservative approach to the specification of seismic siting and design criteria for structures such as nuclear reactors and dams that are critical to public safety. Perhaps we can become less conservative as we learn more from research studies and from experiences during major earthquakes in the future.

In those few areas where large earthquakes are not clearly related to surficial geological structures, such as in the eastern United States, the problem of assigning the maximum credible earthquake is a particularly difficult one to which there are presently no very satisfactory answers. Two of the largest and most disastrous earthquake occurrences in American history were in Missouri (1812) and South Carolina (1886), regions otherwise characterized by relatively infrequent shocks. Not only is this a perplexing problem for geologists, who are as yet unable to relate these events to obvious geologic

Complex zone of surface fracturing along a branch of the Atacama fault in northern Chile. The width of the fissured zone beyond the jeep (center) is at least 100 meters. The last major earthquake here was prehistoric, but the next large earthquake will probably again be associated with similar complex fracturing.





Complex faulting in alluvium associated with the great 1957 Mongolian earthquake is shown at the left. The 280-km-long fault zone was very complicated in places, although in the area of greatest horizontal displacement—8.85 meters (below)—the trace was relatively simple. (Photographs by V. Solonenko)

causes, but engineers are put in the very difficult position of having to decide whether these two areas are really any more hazardous than other parts of the eastern United States that do not happen to have recorded a similar great earthquake within the relatively short historic record. Could a great earthquake such as hit Charleston in 1886 just as well hit Washington, D.C., tomorrow?

This problem will probably never be solved until we gain a much more thorough understanding of how and why earthquakes occur. In the meantime, it may well be that nuclear reactors built in California will be seismically *safer* than those built on the East Coast, simply because we will have a better understanding—however incomplete—of what the seismic hazard is in California that must be designed against.

Particularly in the case of strike-slip faults, fracturing at the surface during a large earthquake is likely to be confined to a single well-defined fault plane without a myriad of auxiliary branching faults. Nevertheless, complicated zones of surface breakage do sometimes form, and this problem of branch or "splinter" faulting has been one of the greatest sources of difficulty in the recent California controversies. No one has knowingly contemplated building a reactor directly astride the most obvious break of a major active fault zone, but how far away from this line must one be to avoid possible branch or splinter fractures? This is a particularly difficult problem when it is considered that almost no location in California is very far from a fault that might be considered active by someone's criteria. Auxiliary faulting is not as random in occurrence as some people have implied, and the geologist can make several constructive contributions to the problem:

(1) Although auxiliary fractures have sometimes been observed during earthquakes several tens of kilometers away from the master fault (e.g., Mongolia, 1957), these breaks have usually occurred on or in close association with pre-existing faults that could have been recognized by geologists prior to the earthquake. Completely new fractures at such distances are rare, particularly in bedrock.

(2) Segments of fault zones in which complex surface fracturing tends to be uniformly distributed over a width of perhaps several hnudred meters can usually be recognized by evidence from previous earthquakes.

(3) Particularly with vertical displacements, complex surface fissuring is more likely in areas of thick alluvium than in bedrock. Strike-slip faults often have relatively simple surface expression even in areas of thick alluvium, and the straighter the fault trace, the less likelihood of auxiliary faulting.

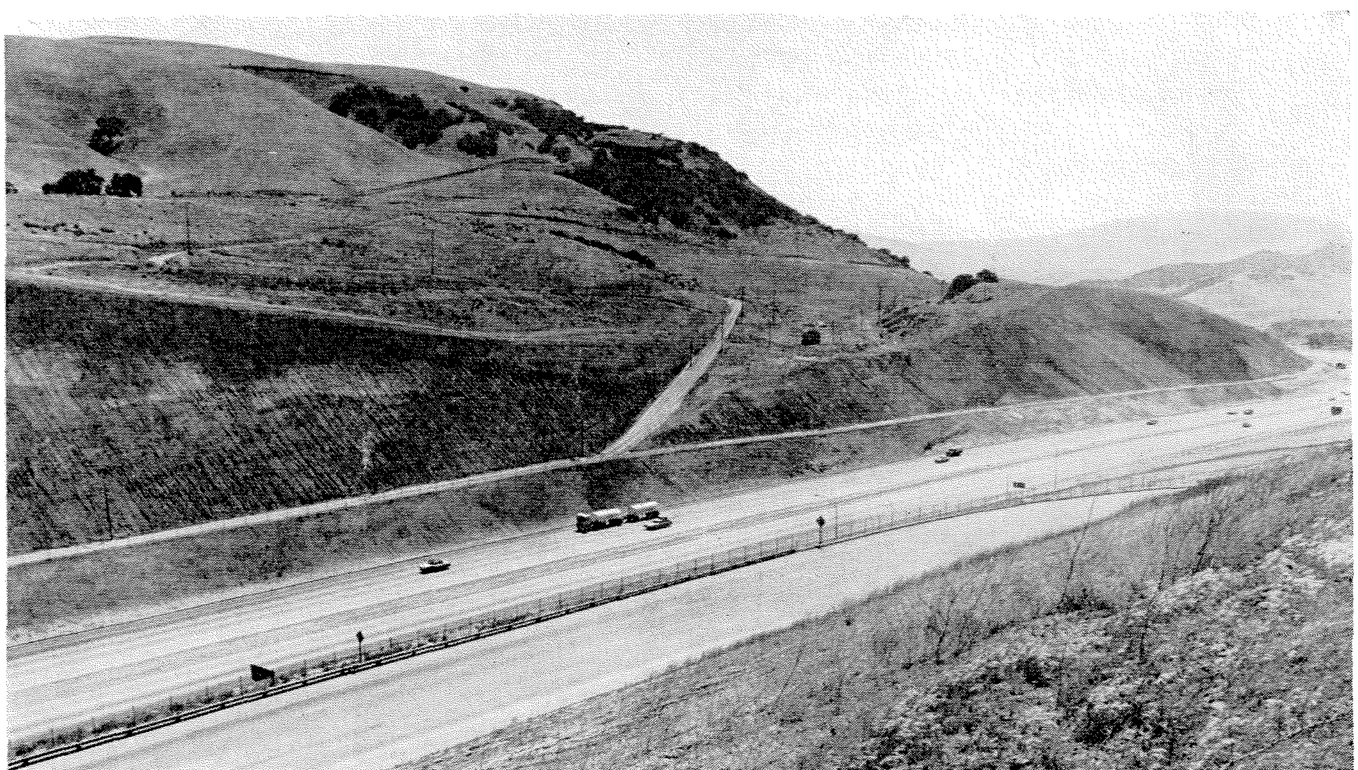
(4) Fault displacements on branch faults are generally only a fraction of those on the master fractures, and thus more easily accommodated in engineering design.

(5) Many features that have been called branch faults in the past were in reality the results of massive landsliding, and hazardous landslide areas can usually be avoided by judicious planning.

(6) Both descriptions and photographs of past large earthquakes associated with faulting have seemingly given undue emphasis to areas of complex surface fissuring as compared with the less spectacular, but often much more extensive, areas of relatively simple faulting.

It must be emphasized that it is often possible for the geologist to say with some degree of confidence exactly where within the width of a wide fault zone the next displacement is likely to take place. This is because the physiographic evidence of recent faulting indicates in many cases that all of the most recent breaks, for perhaps the last few thousand years, have taken place along the same plane within the fault zone, so the next break will probably follow the same path. Thus, despite the fact that many major fault zones are several kilometers wide, with broken and crushed rock exhibited over a broad area, the seismic hazard from faulting in the foreseeable future is usually limited to one or two major planes within the zone. For example, two earthquakes on the San Andreas fault in 1966 were associated with surface faulting along the exact line of earlier breaks, and despite the great width of the fault zone, geologists could have (and indeed *had*) delimited these potential lines of dislocation within one or two meters.

On a broader scale it must be recognized that within tectonically active areas such as California



Despite the great width of pulverized rocks exposed in this new freeway cut through the San Andreas fault at Tejon Pass near Gorman, geologists expect the next displacement to occur along a line passing through the dark zone behind the truck because this is where displacements have occurred in the recent geologic past.

and Japan, almost all rocks—and particularly those of greater geologic age—will show some degree of faulting and fracturing. A completely unbroken block the size of a nuclear facility is virtually impossible to find. But by concentrating his attention on those rocks that have been broken most recently, the geologist can usually specify where the most active and where the most quiescent areas are at the present time.

Whereas the local geology is all-important in attempting to decide whether a given site is subject to possible fault displacement during an earthquake, the assignment of seismic hazard due to shaking is a very different problem. Many studies indicate that heavy shaking during a great earthquake is distributed over a very wide region. In much of coastal California it appears that local soil conditions are more important in establishing the hazard from seismic shaking than is the proximity to the San Andreas or other major active faults. One should not forget that the city of Anchorage, which suffered major damage during the 1964 Alaskan earthquake, was about 130 kilometers from the epicenter—more than twice as far as is the center of Los Angeles from the San Andreas fault.

Clearly there are many needs that must be met if we are to succeed in establishing adequate geological and seismological criteria for the siting of nuclear facilities, both in terms of present practice and in terms of research for the future. Even at the present time, for example, there needs to be an increased understanding of the necessity for thorough geological and geophysical investigations before the commitment is made to build a nuclear facility at a particular site.

Too often in the past, far more time and talent have been expended in defending particular sites than in choosing them. But unless we rapidly gain more basic information about the nature of earthquakes and their geologic effects, it is clear that the geological-seismological field will increasingly become the stumbling block in the construction of nuclear facilities in seismic areas, regardless of how much is known of the geological details at the particular site; this has already been amply demonstrated in the California controversies.

The engineer now appears to be in a much better position to design adequately for any specified seismic event than is the geologist or seismologist prepared to tell him just what that specified event should be! This state of affairs points up the need for vigorous research in a number of closely related fields:

(1) We know very little about the recent geologic histories of major fault zones, yet it is obvious that these histories must be understood if we are to be able to say how *old* a fault is, how *recently* and how *frequently* it has slipped in the past, and how *likely* it is to slip again. Imaginative efforts must be made to use geochemical techniques of absolute age determination and quantitative geomorphology to establish the chronology of events on major active faults, as well as any other techniques that will lead to a better understanding of the mechanics and sequence of events in surface faulting.

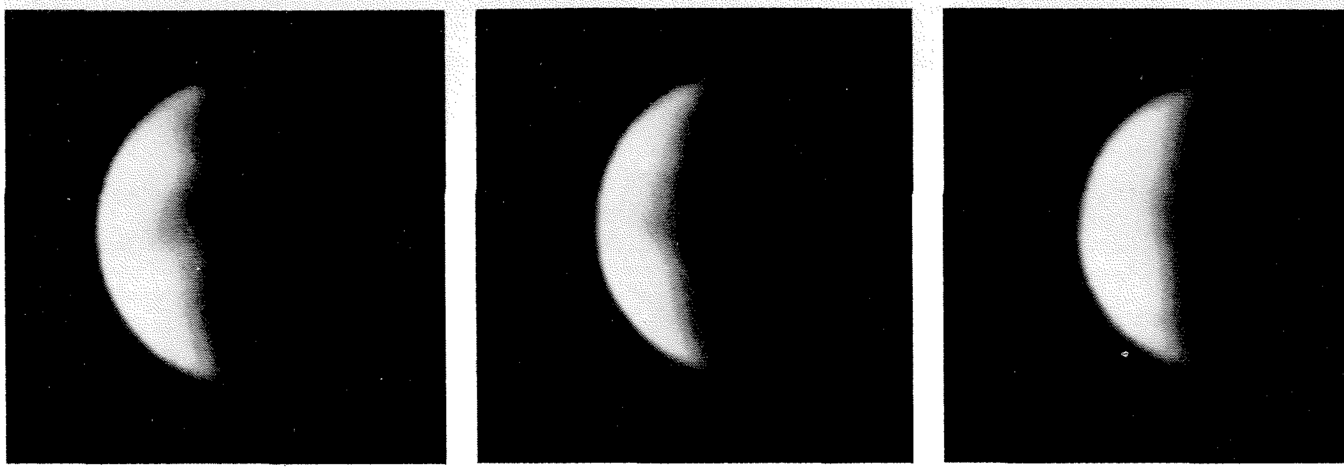
(2) We need better documentation of what actually happens at the earth's surface along faults during major earthquakes, particularly with regard to the problem of auxiliary or branch faulting. This demands careful mapping of surface fractures associated with major earthquakes anywhere in the world.

(3) Good earthquake statistics are available for many parts of the world, but we have little idea of how to interpret these in terms of future expectancy. Aside from the statistical problem itself, a major stumbling block is our lack of understanding as to earthquake *mechanics*. Field, theoretical, or laboratory studies bearing on this question will hopefully enable us better to evaluate future probabilities.

(4) The relationship between seismicity and geologic structure obviously varies from one part of the world to another, and it is important that we try to understand these differences and the reasons for them, particularly if we are to be able to plan adequate nuclear programs in developing areas where the historic seismic record is limited.

(5) Earthquake prediction is a long-range goal that obviously has great import to society. Large national programs in this field are now under way in several countries, and they deserve the vigorous support of the engineering and scientific professions.

(6) In a more philosophic vein, both the engineer and the geologist-seismologist need a better understanding, or a better statement, of what risks society is willing to accept with facilities such as nuclear reactors. It should not be up to the geologist, for example, to have to define "safety" and to prescribe an acceptable level of risk for a given site, yet this problem has been at the core of much of the argument in the recent California hearings. All human endeavors involve some element of risk, and we must be prepared to accept this with nuclear installations. It is neither fair nor proper, however, to ask the scientific and engineering professions to take the sole responsibility for establishing and defending this level of risk.



The Mountains of Venus

by Richard M. Goldstein

Venus well deserves its sobriquet of *mystery planet*. The dense clouds that perpetually cover Venus have prevented man from ever seeing the surface below. Of course, Earth's other planetary neighbors hold many secrets, and the accumulated observations of science and technology have yielded only the scantiest data. But compared to them, and despite Venus' occasional much nearer approach to Earth, the almost featureless clouds have successfully preserved Venus' enigmatic status.

Because of this one might think that Venus would not be a fertile field for geological investigations. However, some observations do exist, and they lead to rather bizarre and conflicting interpretations. The clouds themselves presented the earliest observations. They are very bright, reflecting almost all of the visible rays of the incident sunlight. By analogy with the clouds of Earth, astronomers at the turn of this century decided that the clouds must be made of water. And since no break in the clouds had ever been observed, they concluded that the clouds were very thick and that, consequently, the abundance of water on Venus was very great. The presence of so much water suggested that Venus was a steamy swamp, perhaps populated as are our own rain forests.

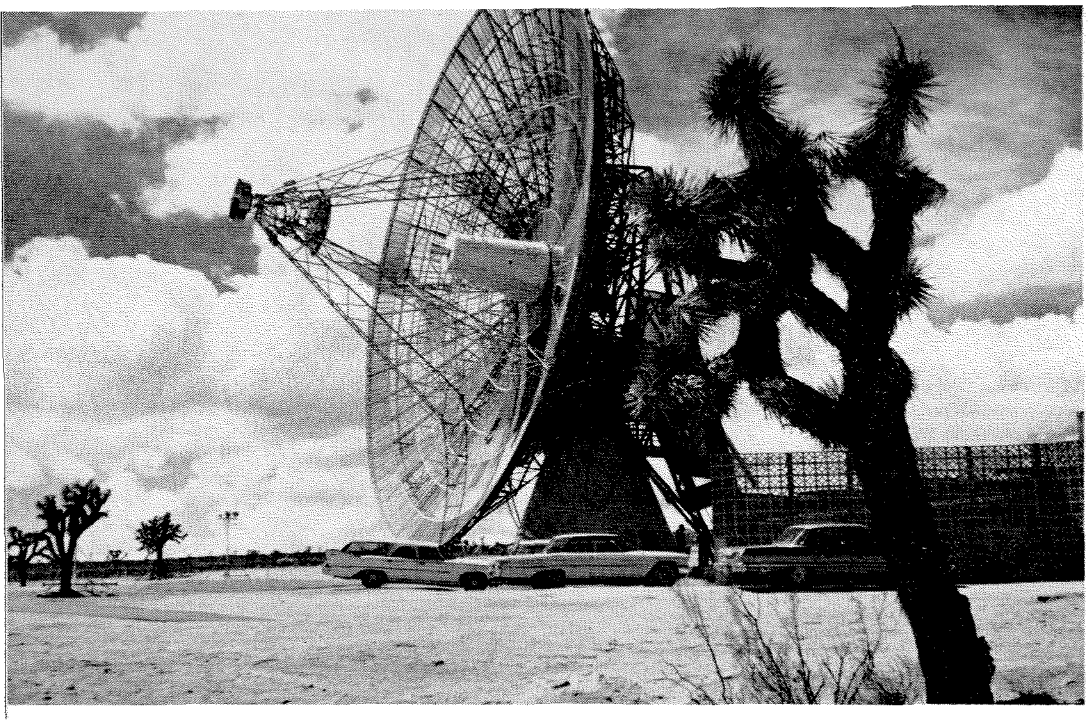
To test this argument spectroscopic studies were made to detect the characteristic signature of water vapor in the reflected sunlight. The early attempts failed to find any water vapor at all, and only the latest measurements show that, at least in the upper atmosphere, there is a very small amount of it.

But if the clouds are not water, what are they? An alternate idea arose that they are dust clouds, permanently stirred up from the surface by strong winds. Thus, Venus became a desert planet, dusty, windswept, and probably hot.

This theory gained support in later years from the spectroscopic discovery of large amounts of carbon dioxide in the Venus atmosphere. On our own planet there is an equilibrium maintained between carbon dioxide in the atmosphere and carbonate minerals on the surface. The large amount of carbon dioxide in the atmosphere of Venus was thus taken to indicate the absence of surface water.

A completely opposite point of view was possible and, in keeping with the divergent theories of Venus, was not overlooked. There is the possibility that no minerals are available to react with the carbon dioxide, because the surface is entirely covered by water. In this view Venus is a featureless planet of oceans.

Still another explanation of the large amount of carbon dioxide in the atmosphere makes use of a presumed chemical balance at the time when Venus was formed. In the case of Earth there was an excess of water over hydrocarbons, leading to our atmosphere and oceans. Venus, on the other hand,



At JPL's Goldstone Tracking Station in the Mojave desert, this 85-foot parabolic dish is used for investigations of the surface features of Venus.

may have had a primordial excess of hydrocarbons, which would lead to an atmosphere consisting of carbon dioxide and smog and to oceans of oil.

That four such diverse pictures of the surface conditions on Venus could seriously be entertained at the same time is an indication of the paucity of real data prior to 1956. At that time radio observations at the Naval Research Laboratory disclosed that Venus is very hot, about 600°F. As is usual in such cases this new datum raised more questions than it answered. Why was Venus so hot? The explanations offered agree that some mechanism allows solar energy to enter the atmosphere easily but prevents the resulting heat from radiating away as easily. They disagree markedly on what this mechanism might be.

One such "greenhouse effect" theory is that the carbon dioxide of the atmosphere is responsible. However, it would require very high atmospheric pressure before the temperature could rise to 600°. Another current theory is the so-called "aeolosphere theory." According to this view solar energy is captured in the form of the mechanical energy of great dust storms. These storms lash the surface continuously, generating the needed heat. This heat is retained, so the theory goes, by the insulating action of the dust clouds.

Radar is one of the most recent instruments to be used for planetary investigations, the first echo from Venus having been received in March 1961. The reason for this relatively late planetary fruition of radar lies in the extraordinary capability needed to do the job. Because of radar's inverse 4th power relationship, ten million times more power is required to probe Venus than is needed for the moon. Since 1961 radar capability has improved steadily, and Venus can now be observed at the far point of its orbit—another factor of one thousand in capability.

The radar studies to be discussed here were all performed at JPL's Goldstone Tracking Station in the Mojave high desert, 150 miles from Death Valley and 50 miles from Barstow. The equipment lends itself well to this service since there is a great similarity between a planetary radar system and a deep space command and telemetry system. The current radar parameters are, briefly:

Antenna	85-foot paraboloid
Power	100 kilowatts, continuous
Wavelength	12½ cm.
Noise Temperature	27°K.

Radio waves are beamed toward Venus in a tight cone of only 22′ of arc. Since the largest angle Venus ever subtends from Earth is less than 1′, Venus is almost uniformly illuminated by the beam. Certainly the beam has not enough resolution to discriminate between different areas of Venus, the "mountains" for example.

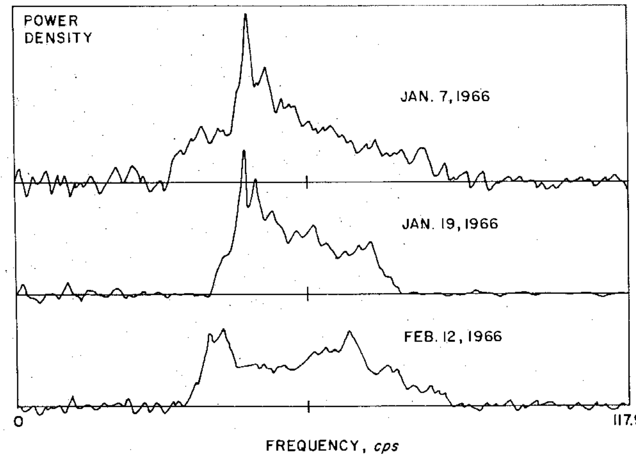
Two methods of obtaining such resolution are available to radar astronomers, however, and they have been used both singly and together. One is time delay. The echo from different areas may return to Earth at different times so that proper signal processing can separate them. Doppler shift is the other. Because Venus rotates, different areas may also have different line-of-sight velocities, hence the echoes will have different frequency shifts. Again, proper signal processing can separate them. In this case signal processing is simply spectral analysis, and the result of an observation is a spectrogram. It is, in effect, the result of scanning Venus with a slit which is parallel to the effective axis of rotation of the planet.

The limit of resolution is set by the oscillator stability of the radar system and by the available signal-to-noise ratio. To date the signal-to-noise ratio limit has always been reached first. Time delay precision of better than 10 microseconds has been achieved, which corresponds to resolution better than 1 mile on the surface of Venus. Frequency precision of 0.1 cycles per second has also been achieved, corresponding to 20-mile resolution on the surface.

The study of the mountains of Venus is closely tied in with the study of Venus' rotation rate. Much like the early days of x-rays and crystallography, the two subjects developed together and each provided insight into the basic nature of the other.

Perhaps at this point the poetic license inherent in the title "mountains" should be mentioned. There is no proof that the objects observed are truly mountains, although mountains are quite consistent with the data. It may be, as the forests are in the Angeles National Forest, that the mountains of Venus are mountains in name only.

The first measurements of the rotation of Venus were made by R. S. Richardson at Mt. Wilson in 1956. He used a spectrographic technique which compared the doppler shifts in the reflected sunlight from the approaching limb of Venus with that from the receding limb. It was a difficult measurement because the solar spectral lines were not narrow enough, Earth's atmosphere severely modified the spectrum, and the rotation of Venus is quite slow. Richardson was able to set an upper limit of 18 days to the period, however.

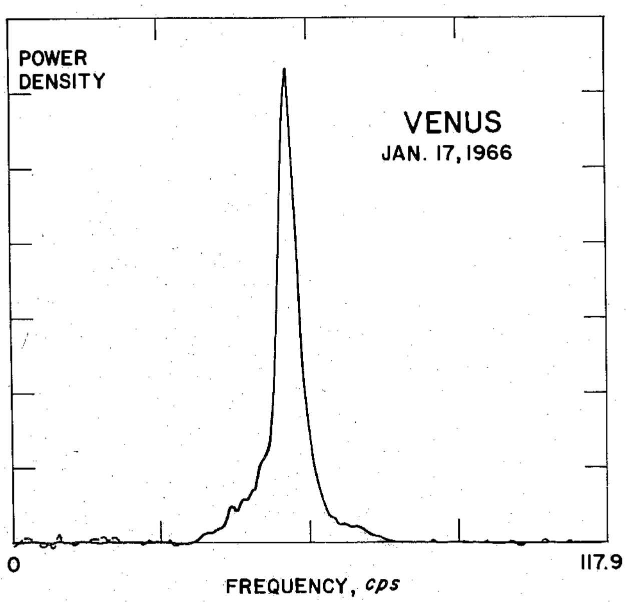


When a spectrogram is depolarized, topographic features can be seen clearly. In this series, peaks move from right to left, corresponding to Venus' rotation.

The early radar measurements of the rotation used the same technique, except microwaves were used instead of visible light. The extraordinarily pure monochromatic radiation available from Earth made the method very much more sensitive.

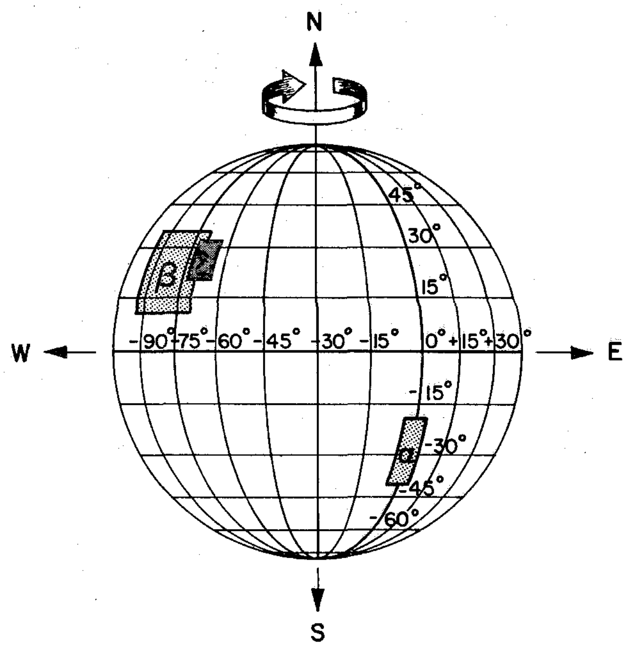
In 1962 the radar studies yielded the surprising period of 250 days, but in the retrograde direction. That is, all of the planets revolve around the sun in the same direction, and all the major planets spin in this same direction—except Venus.

Radar spectrograms show that Venus is very smooth, or shiny, to radio waves. Most of the power has no doppler shift; hence, it has reflected from the central region of the disk. To radar eyes Venus would appear as a disk with a bright highlight at the center and with darkly discernible limbs. Some of the eponymous mountains appear in the spectrogram as faint structures to the left and to the right of the central peak.



Radar spectrogram of Venus, made on January 17, 1966, shows that Venus is smooth to radio waves and would appear as a disk with a bright highlight at the center.

It is evident (left) that the presence of the large peak is similar to a glare that obscures the detail we wish to study. A polarization technique has been very effective in removing this glare. Normally, circularly polarized waves of, say, the right-hand sense are beamed towards Venus. Since a smooth, uniform reflector reverses circularly polarized waves, the receiver is set for the left-hand sense. However, double reflections may be expected to occur from regions that are rough or mountainous. To investigate this possibility the receiver is set for the same polarization as the transmitter. In the resulting spectrogram (above), the "glare" is eliminated, leaving the spectrogram rich in structure. Over successive days of observation the peaks appear on the right and move slowly across the spectrogram,



Schematic map of Venus shows locations of three major features (indicated by α, β, and δ). Two large prominences have also been definitely identified on the other side of the disk, and many smaller ones have been located with less accuracy.

being carried by Venus' rotation. Finally, after several weeks of observation, they disappear on the left.

These are the first data to show that the surface of Venus has relatively permanent features of any kind. If one subscribes to the ocean-covered model of Venus, the possibility of large-scale floating objects comes to mind. To holders of the super-dense atmosphere point of view comes the possibility of formations drifting about with the clouds.

Is it possible to locate these objects on the surface of Venus using the previously measured rotation vector and the motion of the spectral features? And will the deduced location and rotation accurately predict their reappearance at the next set of radar observations, a full 18 months later? The answer is yes. The location that provided a "best fit" to the data taken during the June 1964 inferior conjunction was also a good fit to the "mountains" when they returned to radar view in January 1966 and again in August 1967. Thus, the features are fixed to the solid surface of Venus and rotate with the planet.

The rotation vector gives information about the mountains of Venus. In return, the mountains give information about the rotation vector. Using two years of observations of the features, one can find both their location (above) and the rotation of Venus with surprising accuracy. Our calculations show that the period is 243.0 ± 0.2 days, and still retrograde. Concurrently, the longitudinal extent and location of several prominent features has been fairly accurately determined, the latitudinal extent less so.

Within the uncertainty of ± 0.2 of a day of Venus' rotation period lies a very special number, which we first postulated in 1964, corresponding to synchronism with the earth. Consider an observer on Venus who sees the earth at his zenith at midnight at the time of inferior conjunction. If synchronism holds, he would see the sun rise in the west and set in the east four times; exactly at the fourth midnight the earth would have returned to his zenith. The rotation period required of Venus for this synchronism is 243.16 days. We feel that this remarkable agreement can be no coincidence and that Venus' rotation is synchronized to the earth.

The radar observations have demonstrated that large topographic prominences exist on Venus and that they are fixed to the surface and rotate with the planet. The exact nature of these prominences is unknown. We call them mountains, but there is no assurance that they really are. They may be chains of craters, or features such as the Grand Canyon, or they may be only vast fields of rubble. They do have the ability to alter the polarization microwaves, so they must be rougher than the surrounding area. However, the roughness need only be greater in scale than the wavelength used, which is 12½ cm.

The radar observations also demonstrate that Venus rotates backwards with a period at, or extremely near, synchronism with the earth. It has been inferred from this that Venus must have a large gravity asymmetry (with concomitant internal stresses) and probably a liquid core.

We can now look forward to fairly accurate knowledge of the size and shape of these prominences. Radar data already taken are being processed to yield this information, and observations with the new 210-foot antenna at Goldstone are in the process of being taken.

Other information is in the offing. At the time of this writing Mariner V has just completed a flyby mission on a course to within 2,400 miles of Venus. The important data that we receive from Mariner V will greatly increase our knowledge. Venus is also under intense study from Earth-based optical, infrared, and radio observatories.

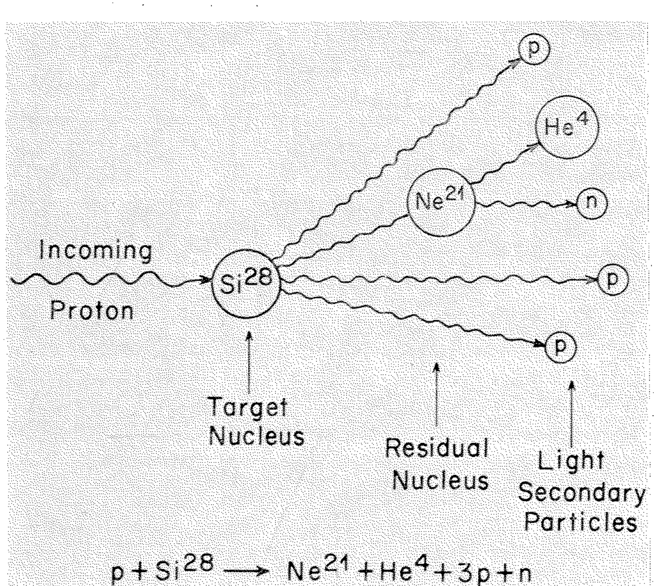
We feel that the time is especially ripe for the geological study of Venus and that we have come to the time where an exponential increase of information will soon provide many of the answers we seek. However, if the past is any guide, each new answer obtained will in turn engender more questions. Venus is likely to remain mysterious for much time to come.

NUCLEAR PROCESSES IN METEORITES

by Donald S. Burnett

In addition to preserving a record of the effects of the decay of long-lived nuclei, meteorites can preserve a record of nuclear processes of a fundamentally different type than occur in terrestrial rock. Study of this record can lead to a nuclear history of the solar system, in the sense that it can provide information on (1) nuclear events which may have occurred during, subsequent to, or even prior to the formation of the solar system, and (2) the physical and chemical processes that have governed the evolution of meteoritic material over the lifetime of the solar system.

Although many investigations have been carried out in various laboratories, it is still too early to tell how firmly this "history" can be established. Many parts of the record are too complex or too garbled to be understandable. The sifting process that might someday lead to unambiguous results is still in progress.



The high-energy nuclear reaction illustrated above is only one of many that may occur between a cosmic ray proton and the constituent nuclei of meteorites. Cosmic ray effects in meteorites are studied by measuring the amounts of such residual nuclei as Ne^{21} *and* He^4.

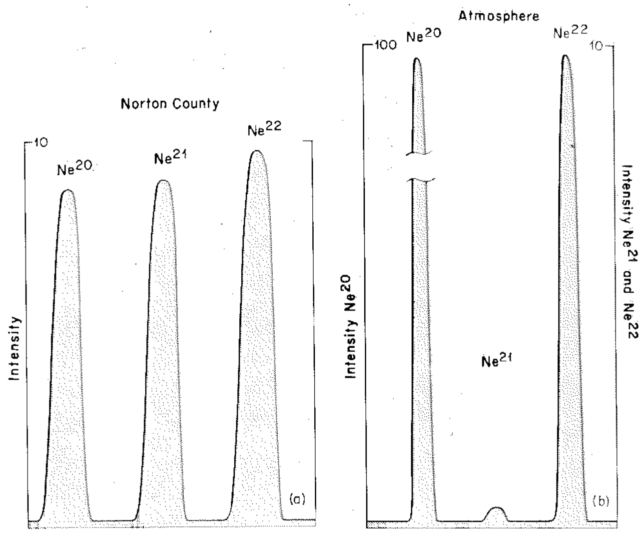
RECENT HISTORY—
EFFECTS OF COSMIC RAY BOMBARDMENT

The protection from cosmic rays given to the surface of the earth by the atmosphere and the geomagnetic field does not exist for a meteorite in interplanetary space. A large fraction of cosmic ray particles (mostly protons) striking a meteorite undergo nuclear reactions with the constituent nuclei of the meteorite (left). Reactions that produce neon or other rare gas isotopes provide an important means of studying the effects of cosmic ray bombardment. At the time the minerals of the meteorite solidified any neon present in the environment was left behind because it is a gas and is chemically inert. Consequently, the neon in the vast majority of meteorites originates as the product of nuclear reactions. Although the amounts of the neon isotopes present are very small, they can be detected separately with a high-sensitivity gas mass spectrometer.

The isotopic composition of the cosmic-ray-produced neon is considerably different from that found in the earth's atmosphere. In the case of the Norton County meteorite, for example, the amount of neon observed corresponds to an exposure time to cosmic rays of roughly 0.2 billion years. On the other hand, utilizing the decay of Rb^{87} to Sr^{87}, G. J. Wasserburg, Caltech professor of geology and geophysics, and I have found that this meteorite crystallized 4.6 billion years ago. The difference in these times means that the meteorite was shielded from cosmic rays by being buried (to depths of a few yards or greater) in a larger body until 0.2 billion years ago, when it was released as a small body (most likely by collisional breakup) and subsequently fell on the earth. Similar measurements from many laboratories have shown that this conclusion is generally true for all meteorites studied to date.

ANCIENT HISTORY—PRIMORDIAL IRRADIATIONS

In addition to cosmic rays, which originate in the galaxy outside our solar system, violent flares on

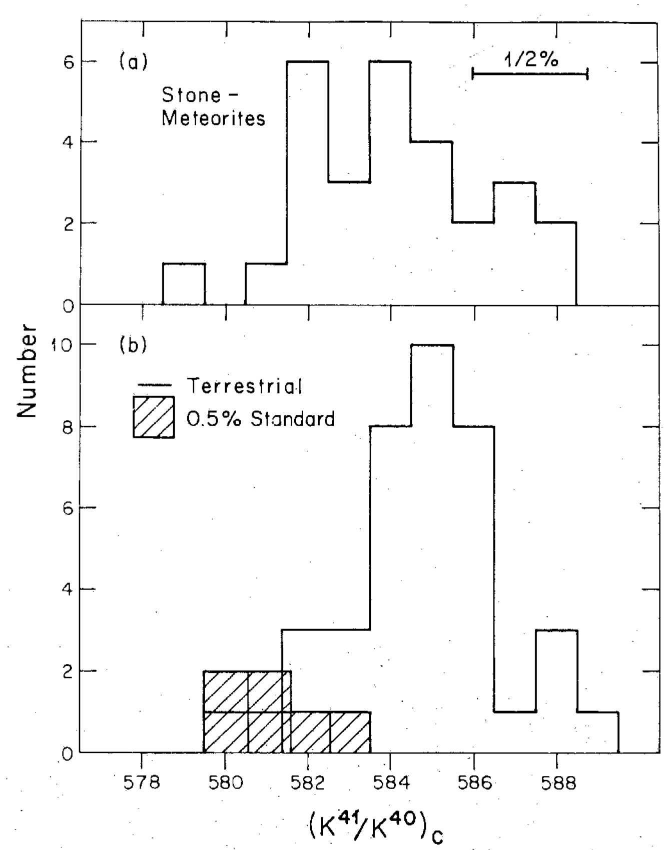


Mass spectrum of neon from the Norton County meteorite (left) and the earth's atmosphere (right). The break in the atmospheric Ne^{20} *peak is to emphasize that* Ne^{20} *is about 10 times more abundant in the earth's atmosphere than* Ne^{22}*. The neon in Norton County originates entirely from cosmic-ray-induced nuclear reactions. The amount of neon in Norton County is about* 50 x 10^{-8}cc *per gram. (Measurements made in collaboration with D. D. Bogard, P. Eberhardt, and G. J. Wasserburg.)*

the surface of the sun have been observed to accelerate particles to sufficient energies to cause nuclear reactions. The present rate of production of solar flare particles with energies comparable to galactic cosmic rays is insufficient to produce significant effects in meteorites, but how far this conclusion can be extrapolated into the past is not known. In particular, there is some basis for speculating that the rate of particle acceleration may have been considerably higher in the past.

Astrophysical observations on objects known as T-Tauri stars indicate that these are very young (only a few million years old) and are still associated with a cloud of gas and dust from which they presumably formed. Moreover, the concentration of lithium on the surface of these stars appears to be at least 10 times greater than it is in the surrounding cloud. Lithium is an element which is thought to be synthesized by nuclear reactions resulting from stellar surface flares; thus these stars appear to be accelerating particles and synthesizing lithium. The T-Tauri stars may be evolving toward stars similar to the sun, so it is possible that the sun (and perhaps all stars) accelerated large numbers of particles in its early evolutionary phases. Whether or not meteorite investigations can shed any light on the existence of such an event depends on what is assumed about the state of the solar system at the time of irradiation.

Without discussing specific models, one can say that if the materials that eventually formed the earth and formed the meteorites had sufficiently different histories of irradiation or subsequent mixing, then variations in the isotopic composition of certain sensitive elements might result. For example, meteorites may have formed from material that was further from the sun and therefore experienced less irradiation. The very low abundance of K^{40} relative to the other potassium isotopes, K^{39} and K^{41}, and to other neighboring elements makes it quite sensitive to various types of irradiation because it takes only a small amount of reaction to produce a measurable effect in K^{40}. However, our studies showed that no difference could be observed in the isotopic abundance of K^{40} in terrestrial and meteoritic samples. Quantitative interpretation requires a more detailed discussion about the conditions of irradiation; however, no positive evidence for any large-scale particle irradiations could be found. Similar investigations in other laboratories on the elements Li, Gd, S, and Cr came to the same conclusion. But all these studies are only sensitive to *differences* in the conditions of irradiation between terrestrial and me-



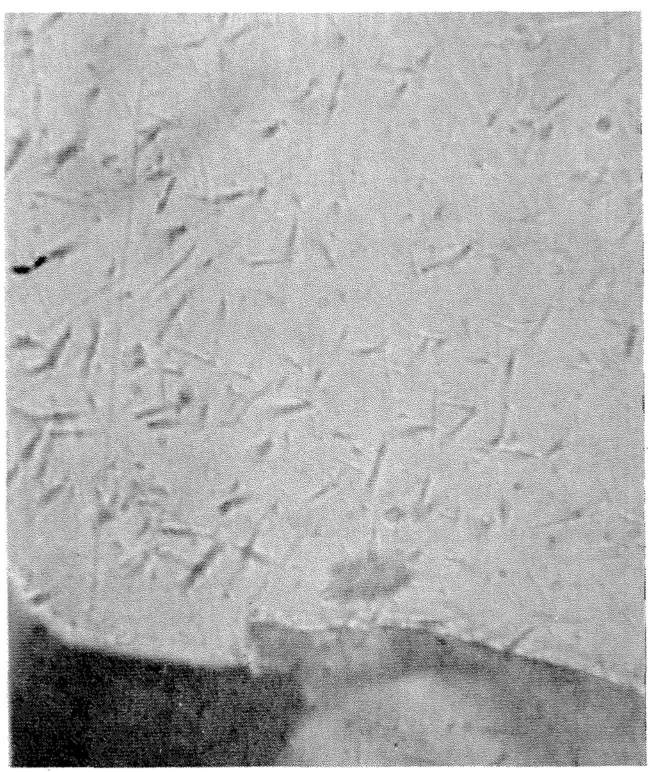
The measured ratio of K^{41} *to* K^{40} *in a variety of meteoritic (a) and terrestrial (b) samples. No distinction in the* K^{41}/K^{40} *ratios in the two types of material could be detected. The sensitivity of the mass spectrometric measurements is shown by the cross-hatched squares, which are measurements of a standard which was enriched in* K^{40} *by 0.5%. (Measurements made in collaboration with H. J. Lippolt and G. J. Wasserburg.)*

teoritic material and can only place limits on the way in which such irradiations would have to occur.

NUCLEAR PREHISTORY—
NUCLEOSYNTHESIS AND EXTINCT NUCLEI

Although meteorites give no evidence for strong nuclear activity within our solar system during its formation, they do contain a record of large-scale nuclear events that occurred prior to this time. The synthesis of the various chemical elements from hydrogen by chains of nuclear reactions is generally believed to occur in the interiors of stars and in supernova explosions. In addition to the stable nuclei which remain today, these processes produce a large number of unstable radioactive nuclei. Some of these, such as K^{40}, Rb^{87}, and U^{235}, decay slowly and exist in nature today. Nuclei with intermediate lifetimes can exist through the time interval following the events of nucleosynthesis until the formation of solid bodies in the solar system, but they cannot survive the intervening 4.6 billion years.

Strong evidence exists for the presence of two such "extinct nuclei"—Pu^{244} (with a half-life of 82 million years) and I^{129} (half-life of 17 million years) —when meteoritic material was formed. I^{129} decays to Xe^{129}, an isotope of the rare gas xenon. Very little xenon, like neon, was incorporated into the meteorites when they formed; the Xe^{129} formed from I^{129} decay can produce a striking excess of this isotope in meteoritic Xe. Following its discovery by J. H. Reynolds at Berkeley, excess Xe^{129} has been found in a large number of meteorites.



Fission tracks in a crystal of the mineral diopside from the Four Corners meteorite. The tracks presumably arise from the spontaneous fission decay of the now-extinct Pu^{244}. The number of tracks shown corresponds to a density of 6,000,000 tracks per square cm. The dimensions of the picture are roughly 40 by 50 microns.

Pu^{244} decays primarily by the emission of alpha particles, but about 1/1000 of the decays occur by a process known as spontaneous fission in which the Pu^{244} nucleus splits into two large comparable-sized fragments. Evidence for fission processes in meteorites has come from two independent methods:

(1) Roughly 5 to 6 percent of the fission events produce the isotopes Xe^{131-6}. As first demonstrated by Rowe and Kuroda of the University of Arkansas, there is excess Xe^{131-6} in many meteorites, which can almost certainly be attributed to fission.

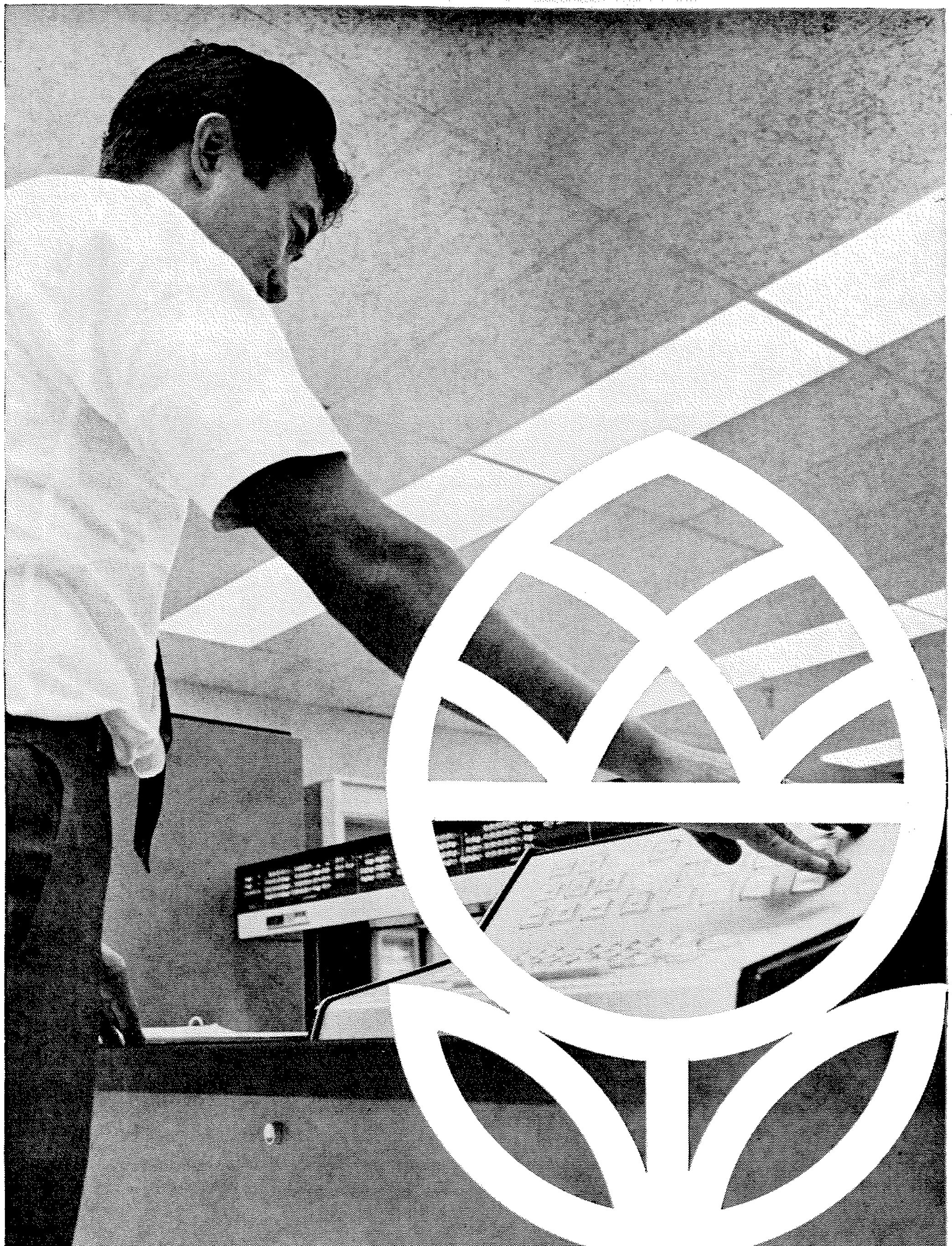
(2) A large amount of energy is given to the fragment, which in turn produces a path of radiation-damaged material in the crystal in which the fission event occurs. This damaged material is much more subject to chemical attack than the bulk material, and treatment with an appropriate etching agent produces a hole or "fission track" along the original path of the fission fragment. As shown by Fleischer, Price, and Walker at the General Electric Research Laboratory, several meteorites contain many more fission tracks than would be expected if Pu^{244} were not present.

The presence of these extinct nuclei almost certainly means that events of nucleosynthesis occurred in an interval of a few hundred million years just prior to the formation of our solar system. The case of I^{129} is somewhat ambiguous, since it could be formed by nuclear reactions during a large-scale irradiation within the solar system; however, corresponding reactions do not exist for Pu^{244}.

Considerable additional insight and experimental data will be needed before the full implications of the presence of the extinct nuclei can be grasped. Nevertheless, their potential usefulness appears very large.

THE ROLE OF RETURNED LUNAR SAMPLES

The moon's surface, regardless of whether it is recent or ancient, undoubtedly contains an analogous record of nuclear processes. If it is old, more information about the early history of the solar system should be obtained. If the surface is recent, it may be possible to learn about the erosional and regenerative processes that caused it to be recent. The exciting aspect of lunar-sample investigation is that, at present, no one appears smart enough to know just what to expect.



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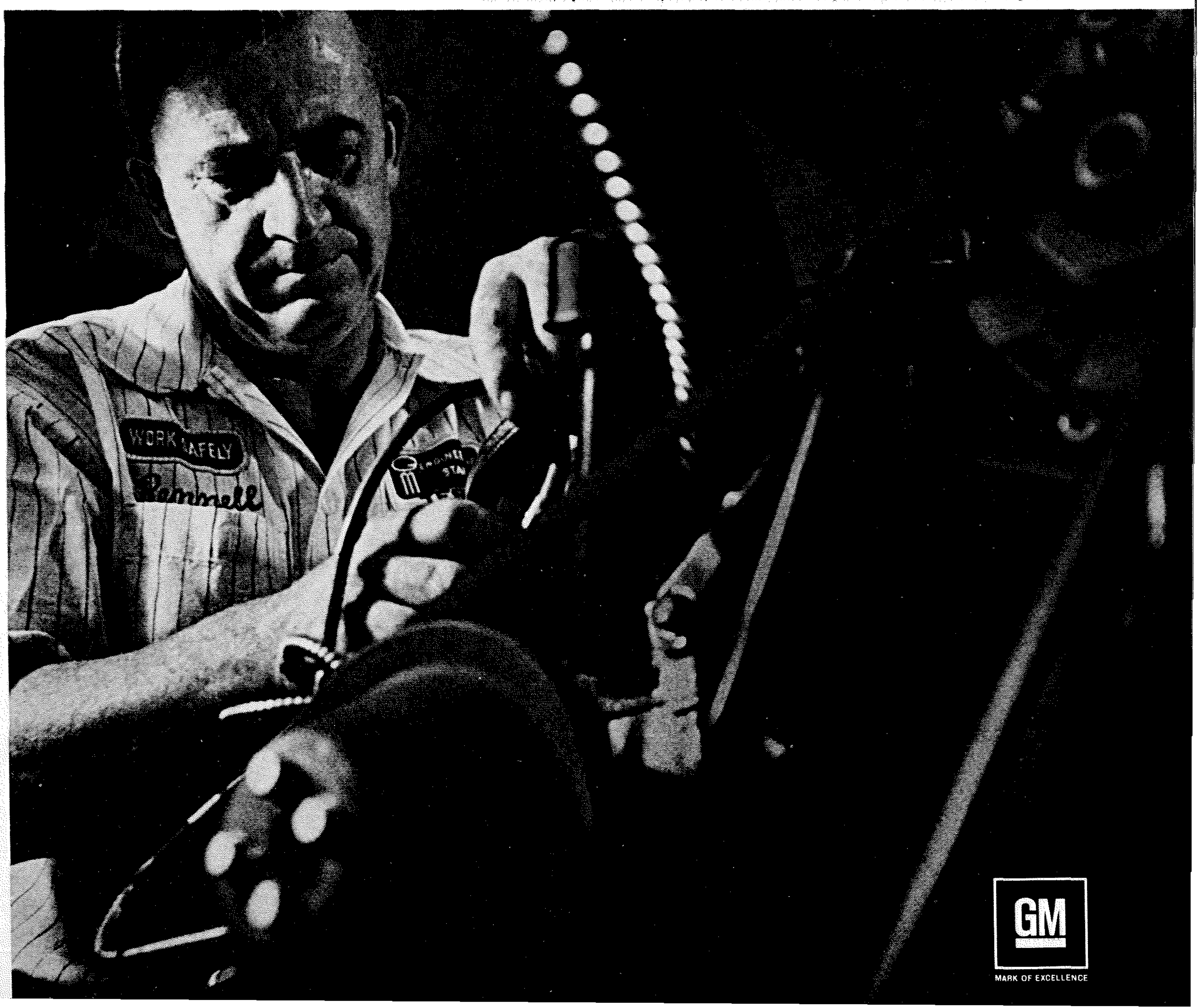


Ice Under Stress and Pressure, Ice In Order and Disorder

by Barclay Kamb

The interest in ice at Caltech goes back at least as far as Linus Pauling's discovery, in 1935, of the important phenomenon of proton disorder in ice and his celebrated explanation of the zero-point entropy of ice. The interest might well go back further still, for what Caltech professor or student, sweltering in Pasadena during the summer months, might not be able to imagine the beauty of field work on ice in Alaska or the Pacific Northwest? But it remained for Bob Sharp to bring any such dreams to realization, with his expeditions to the Seward-Malaspina glacier system in Alaska, beginning in 1948. And it is to Bob that we owe not only the beginning of the work on ice in Caltech's geology division, but also the fostering of a broader view of the geological significance of ice—the significance of its study in the wider context of the rocks and minerals of the earth.

The great pressures at depth in the earth are thought to squeeze the minerals of our everyday experience into novel, super-dense forms. Stresses generated by the forces responsible for earthquakes are thought to deform severely the rocks of the earth's crust and mantle, in the processes by which mountain ranges and other great earth structures are built. In the world of ice, there is a rich variety of similar phenomena. Several dense ice phases are produced by transformations under pressure, and glacier ice is involved in extreme effects of solid deformation. In ice we have a solid-state system exhibiting in classic form the phenomena in which solids respond to pressure and stress.

In the study of ice and its response to pressure and stress, our approach at Caltech was first and foremost a field effort—an observational approach. But the subject has also developed very rapidly along theoretical and experimental lines in recent years, and we are contributing to this aspect too. Several years ago we began experimental work on ice polymorphism under pressure. Now we have completed construction of a cold laboratory for research on the response of ice to stress. This work had its origins in 1960 when I carried out, in Switzerland, the experiments that are the basis for some of the information presented here and that provide the starting point for the experimental program of the new cold lab. Some other aspects reported in this article are the result of experiments done in collaboration with William F. Brace at MIT, while I was visiting professor there last fall. And in the field program we have had valuable collaborations with Ronald L. Shreve ('52, PhD '57) of UCLA and Edward R. LaChapelle of the University of Washington. Much of the work described here has been supported by the National Science Foundation, the Guggenheim Foundation, and the Sloan Foundation.

ICE UNDER PRESSURE

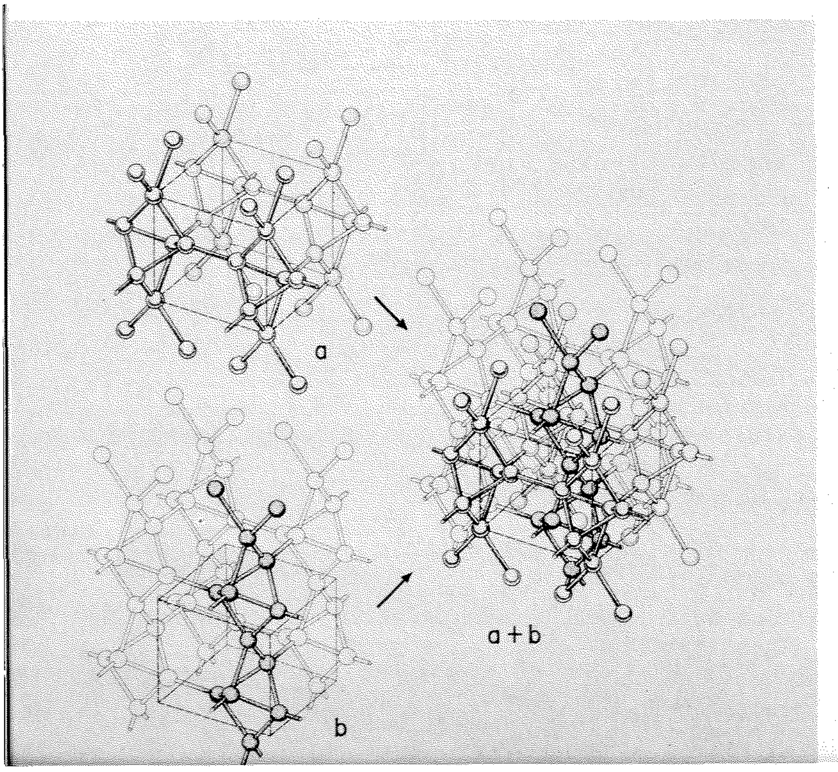
The effects of pressure on ice are in a sense the most basic. Pressure is, of course, the simplest type of stress—the isotropic one. Whereas the response to non-hydrostatic stress often involves complex irreversible phenomena, the response to hydrostatic pressure is governed by equilibrium thermodynamics and brings into evidence the basic equilibrium thermodynamic properties of the H_2O system. These properties are in turn a macroscopic reflection of the underlying structural architecture on the molecular scale—the mechanism of bonding, the nature of the intermolecular forces, and their resistance to bond deformations of various kinds. Application of pressure causes structural collapse, either by simple self-compression, which involves a more-or-less uniform bond shortening, or else by thorough structural reorganizations representing transformations to denser phases. Ordinary ice I transforms at about 2,000 atmospheres to the denser phases ice II or ice III, and these transform at higher pressures to still denser phases. In all, twelve distinct phases of ice are now recognizable, of which nine are produced at high pressure.

The water molecules in ice I behave tetrahedrally, each molecule forming four hydrogen bonds to neighbors in tetrahedral directions. Because of this tetrahedral geometry, there is an analogy between possible ice structures and structures of silica minerals; and, indeed, ice I is the structural analog of one of the SiO_2 polymorphs, tridymite. Whether the tetrahedral character of the water molecule is retained under the collapse brought about by pressure, and whether the structural analogy with silica polymorphs continues to hold in the dense forms of ice, had to be discovered by determining the structures of the high-pressure phases. Before we began our crystallographic study of the high-pressure forms of ice, it had been proposed that in the dense ice phases hydrogen and oxygen become dissociated as separate H^+ and $O^=$ ions. The implied change from an intermolecular type of crystal bonding (hydrogen bonding) in ice I, to an ionic type of bonding for the dense ice phases is a very drastic change in the nature of the bonding forces—one that would have to involve a complete reorganization of the electronic structure.

Our crystallographic studies of the high-pressure ices make use of the trick of quenching. The ice is made in a bomb at the appropriate pressure and temperature, and the bomb is then cooled to -196°C by immersion in liquid nitrogen. At this temperature the dense ice does not invert to ice I upon release of pressure but remains metastabily in the dense form. The samples can be extracted from the bomb, and individual crystals can be studied by x-ray diffraction as long as they are kept at low temperature.

The type of result obtained is shown for ice VI, below. We find that the integrity of the individual water molecules is retained in the dense phases; there is no dissociation into H^+ and $O^=$ ions. Except at the highest pressures, four-fold coordination of the water molecules remains the basic structural feature, and in this sense the water molecule retains its tetrahedral bonding character. But angular distortions from the ideal tetrahedral bond arrangement of ice I become very large. While the structural analogy with polymorphs of silica remains possible, only one of the dense ice structures is a straightforward analog of a form of silica. But ice VI can be considered the analog of the silicate framework of a zeolite if only half of the structure (part a or b of the drawing below) is considered. Here we see a novel structural feature of some of the dense ice phases: the structure is built up of two separate, independently bonded frameworks, each occupying void space in the other. Surprisingly, no structural analog of quartz—the common form of SiO_2—occurs among the dense forms of ice. The phase diagrams and thermodynamics of the SiO_2 and H_2O systems, in relation to structure, are in fact very different. This probably reflects a marked difference in the energetics of bond-bending in the two groups of stuctures, as might be expected from the different nature of the bonding forces.

In the drawing of ice VI (left), the hydrogen



How to construct a dense form of ice (ice VI). Water molecules (balls) are hydrogen-bonded together (sticks) to make the two complete frameworks, a *and* b *at the left. These are then combined within the same space to form the complete structure* a + b. *Hydrogen atoms are in a disordered arrangement and are not shown here. They are present statistically near one or the other end of each bond.*

(Illustration reproduced from Science, vol. 150, p. 208, copyright 1965, American Association for the Advancement of Science.)

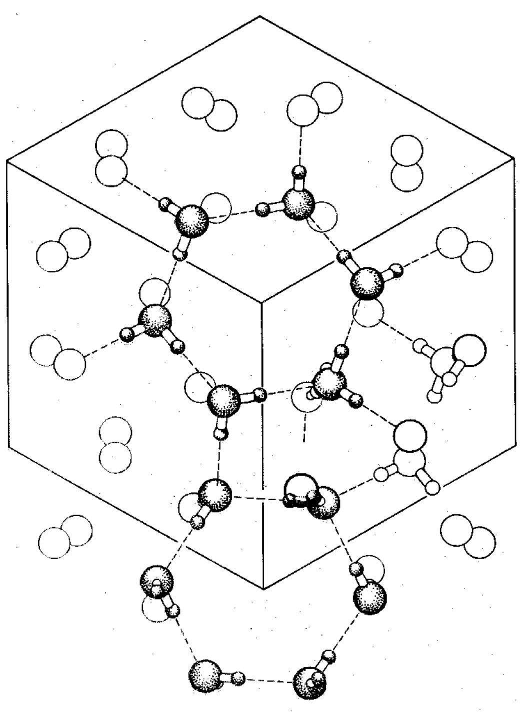
atoms are omitted because they do not occupy fixed positions but instead are involved in proton disorder—the phenomenon discovered originally in ice I by Pauling. Each water molecule assumes at random any one of six orientations consistent with the network of hydrogen bonding, and in each bond a proton appears at random near one end of the bond or the other. In ice I the disordered arrangement does not "order up" on cooling, but we have evidence suggesting that in ice VI, such an ordering-up does occur. In ice II the tendency toward proton-ordering is so strong that only an ordered structure occurs (below), and there is no disordering at higher temperatures. Because of the proton order, the entropy of ice II is 0.8 entropy units less than that of ice I, in striking confirmation of Pauling's original calculation of 0.81 entropy units as the entropy of proton disorder in ice I.

The state of order or disorder of the protons has decisive consequences for the physical properties of the ice phases, especially for the electrical properties. The high dielectric constant and the dielectric relaxation of ice I have long been known and admired; they are made possible by the ability of the water molecules in the proton-disordered crystal to change from one orientation to another under the influence of an external electric field. Ice VI has a high dielectric constant and shows dielectric relaxation, whereas ice II has a low dielectric constant without any relaxation.

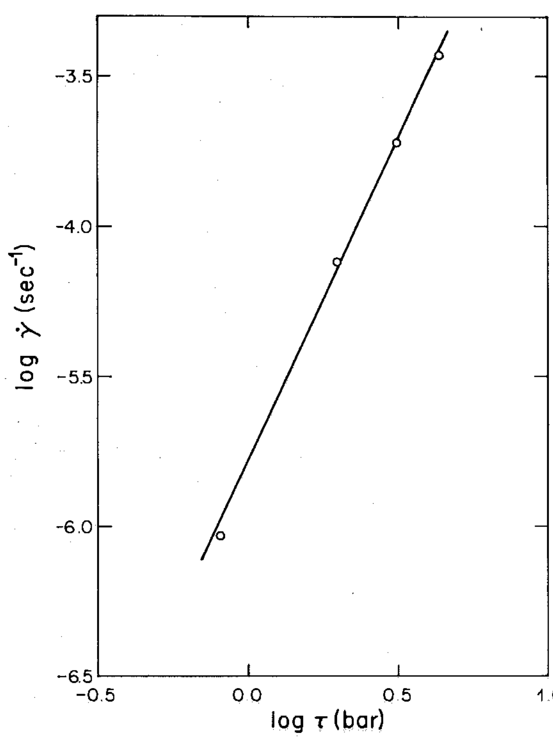
Highly sheared crystal of ice I. The sloping reference lines (arrows) were originally vertical, but were tilted through an angle of 72 degrees by plastic flow in the crystal, as shown. The total shear strain is 310 percent. The crystal is 8 cm in diameter.

ICE UNDER STRESS

The response of ice to stress, as distinct from simple hydrostatic pressure, brings forth new and interesting phenomena. The celebrated plasticity or flow-response of crystals of ordinary ice I (above) takes place through the motion of defects (dislocations) in the crystalline structure and has some puzzling features—notably the extreme anisotropy (the strength varying by more than three orders of magnitude in different directions) and the prominent nonlinearity of the response (below), which shows up strongly in flow measurements on glaciers. If the motion of dislocations is controlled primarily by the



A proton-ordered form of ice (ice II). The protons of the individual water molecules are in definite positions; the hydrogen bonds are indicated by dashed lines.



Relation between applied shear stress τ and strain rate $\dot{\gamma}$ for the ice crystal shown at top of page. If the response were linear, the line would slope at 45 degrees.

ability of the water molecules to rotate from one orientation to another, one might expect a close tie between stress response and electrical response. The dielectric relaxation time in ice III is about 1/100th that in ice I at the same temperature, apparently because the energy barriers to rotation are reduced in the distorted tetrahedral configuration of the denser ice structure. In a recent experiment at MIT, W. F. Brace and I found that ice III is at least two orders of magnitude more plastic than ice I. This discovery suggests a close relation between the electrical and flow phenomena. We plan soon to extend the comparison to ice II, which, according to these ideas, should show little or no plastic response to stress.

IMPLICATIONS

What is the relevance of these ideas of structural reorganization, of response to pressure and stress, of proton order and disorder, for the world of ice as we know it on the earth? The whole subject of how glaciers flow and of how they respond to climatic changes is, of course, intimately concerned with the stress-response of ice. And if transitions to ice II or ice III were to occur, the behavior of the glaciers would be enormously affected. But the thickest ice on earth, 3.5 km in Antarctica, falls far short of the 22 km required to produce ice II or ice III. The required thickness was not approached even at the maxima of the ice ages. (It might, however, be present on Jupiter and Saturn.) The relevance, then, is indirect—the insight into ordinary ice I that is obtainable from interrelationships of structure and physical properties among all of the ice phases. This is clearly seen in the relation between the plasticities of ice I and ice III, which has important implications for the mechanism of plastic flow in ice I by itself.

Another example of these interrelations is seen in the phenomenon of elastic relaxation. Below an oscillation frequency of about 1 kc, some of the elastic constants of ice I decrease by about 5 percent from their high-frequency values. This elastic relaxation has been attributed theoretically to a tendency for the protons to assume an ordered configuration in the elastically strained structure. At first sight this interpretation seems dubious, when we consider that in many of the high-pressure ices, with tetrahedral geometry distorted vastly more than ever occurs in elastic strains in ice I, the protons assume a disordered arrangement. But on closer examination one finds that the magnitude of the order-promoting energy (in relation to elastic distortion) required to explain the observed elastic relaxation is comparable to observed proton-ordering energies in relation to distortions of tetrahedral coordination in the high-pressure ices. Thus the observed effects of order and disorder in the high-pressure phases support an order-disorder phenomenon as the cause of elastic relaxation in ice I.

While these examples give some idea of the implications of high-pressure structural information for the world of ice that interests us geologically, it must be admitted that the bridge of interpretation between these two areas of knowledge about ice is far from completely built. It will probably take years to write a coherent story relating ice in its various physical forms and ice in its many natural manifestations. Here I want to jump boldly across this gap and round out the picture of our work on ice at Caltech by telling of some current efforts to understand those impressive natural manifestations of ice, the glaciers.

GLACIERS ON THE MOVE

Our interest at Caltech has tended to concentrate on flow and deformation phenomena in glaciers—on effects of stress and pressure. Lately we have been trying to find out what goes on in that part of the ice nearest the glacier bottom, where the stresses and pressures are the greatest. It is here that the main contributions to glacier motion arise, through rapid plastic deformation of the highly stressed ice near the bottom and through a sliding of the ice mass as a whole over the bedrock underneath. To get information on these effects we have drilled deep boreholes through the ice, have measured the internal deformations taking place, and have brought up core samples to study the structure of the highly stressed ice (*Engineering and Science*, February 1965). We have also excavated tunnels to the glacier bottom, in places where that is feasible, to observe at first hand the sliding of the ice over the rock below.

In the summer of 1967 we carried out a combined attack to study the dynamics of motion in an icefall, a place where ice flow velocities are unusually high (about 0.5 m per day). The study area was a portion of Blue Glacier, our "outdoor laboratory" in Olympic National Park, Washington. The work was a collaborative effort of a Caltech team, led by me, and a University of Washington team led by Edward R. LaChapelle, and was carried out with the cooperation of the U. S. National Park Service.

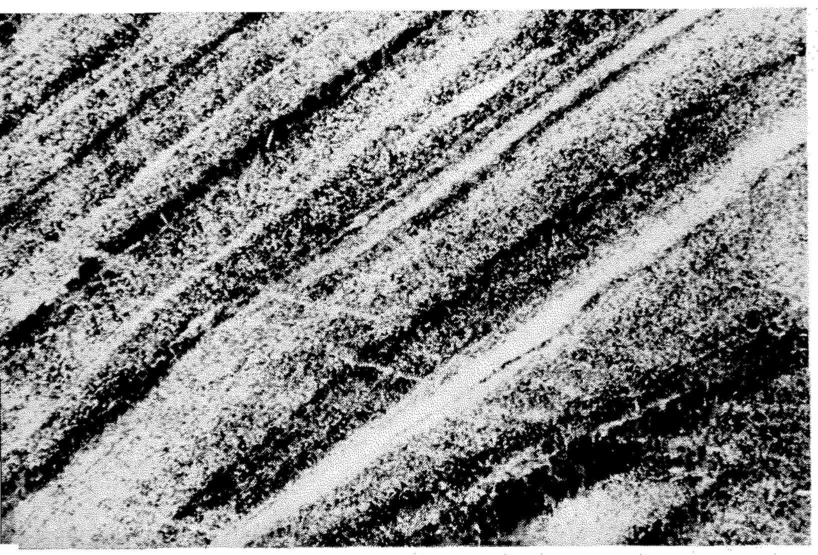
In a portion of the icefall selected for smoothness of flow, tameness of access, and relatively mild hazard from avalanches and collapsing seracs, we drove a 90-meter tunnel from the surface to the bottom of the ice and drilled 10 boreholes to the bottom in a pattern designed to reveal the broader

A portion of the Blue Glacier in Olympic National Park, Washington, showing icefall descending from Mt. Olympus. The Caltech-Washington tunnel entered the ice at the point marked T *and proceeded generally toward the right to the bottom. The boreholes at* B *were drilled vertically downward to strike bedrock near the tunnel head 70 meters below.*

configuration of bedrock in the area of the tunnel head (above). The tunnel was excavated by means of compressed-air-powered chain saws and jackhammers, plus a great amount of plain hard labor. The holes (right) were drilled by means of a thermal borer, and a microswitch sounding device was then used to locate the bottom accurately and to follow changes in its position as the glacier moved along. This was done in order to measure the bed roughness, an important parameter in the relationship sought between basal shear stress and sliding velocity of the glacier.

Another important parameter is the extent of separation between the bedrock and moving ice, due to stresses set up in the flow process (subglacial "cavitation"). To observe this we built a camera that could take pictures of the walls of the two-inch-diameter boreholes. With this instrument we could locate the base of the ice and measure the gap be-

A drill site in the icefall. Barclay Kamb is preparing to lower the borehole camera to determine ice separation at the base of the glacier.



Ice in the tunnel wall near the base of the glacier. The laminated structure is parallel to the flow direction of the ice. Area photographed is 2 ft. long.

tween ice and bedrock. These measurements and observations are "firsts" in the study of glaciers; no one had tried to measure subglacial roughness before, and no one had put an "eye" deep into a glacier before.

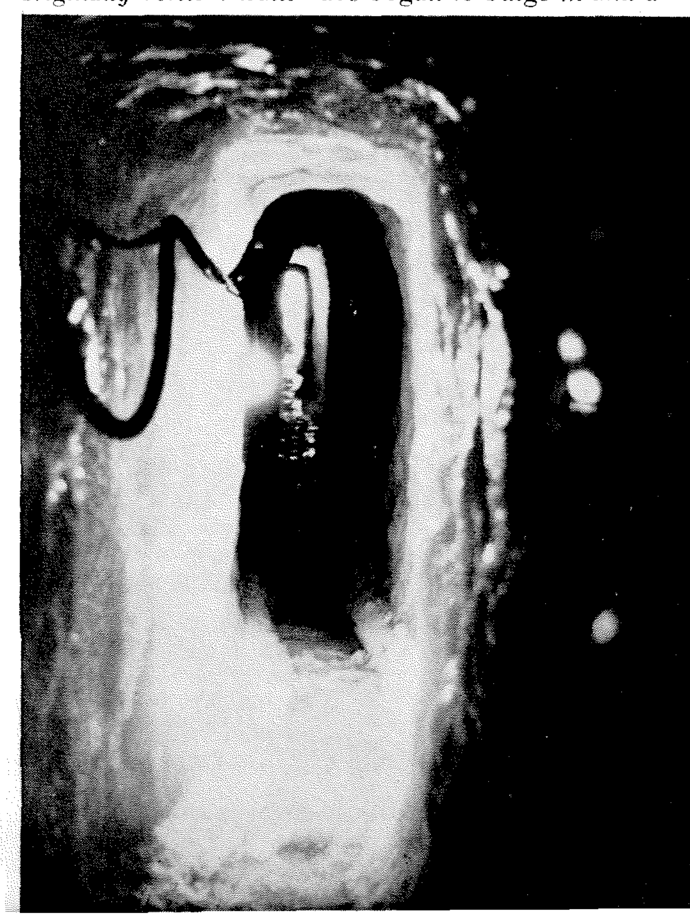
AN INSIDE VIEW

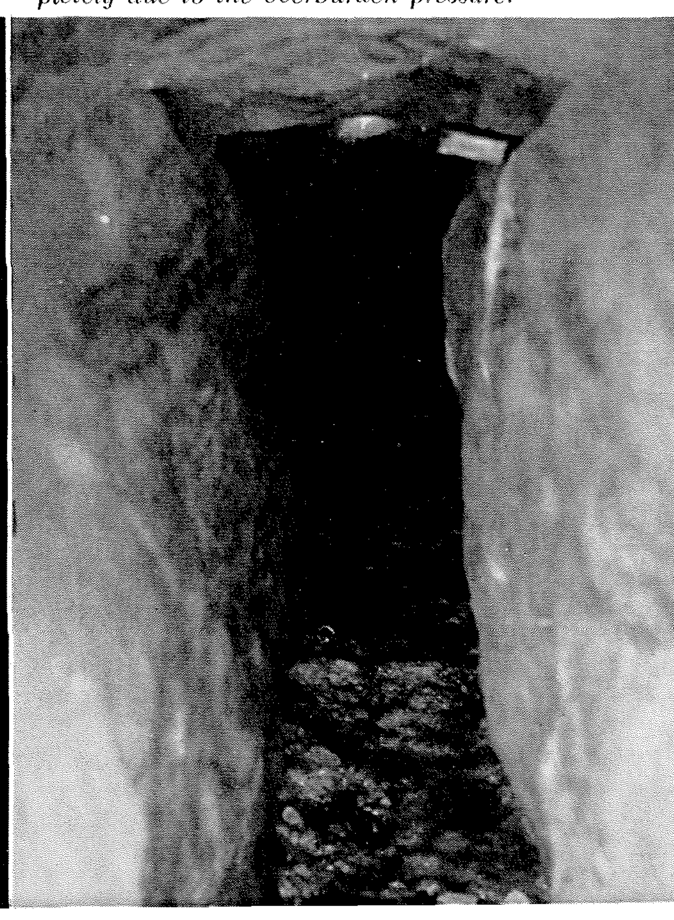
The best view was, however, the one from inside the tunnel. In exposures on the tunnel walls one could trace, from the surface inward, a striking transition from the jumbled, chaotic ice near the surface to ice at depth having a very orderly structure with beautiful laminations aligned along the flow direction (left). This orderly structure is produced by deformation under the high stresses in the deep ice. Another effect of stress is an aligning of the individual ice crystals into certain definite orientations with respect to the flow direction. These changes from disorder to an orderly structure in glacier ice under stress are reminiscent, on the macroscopic scale, of the proton order induced under pressure and stress within individual crystals, on the microscopic scale.

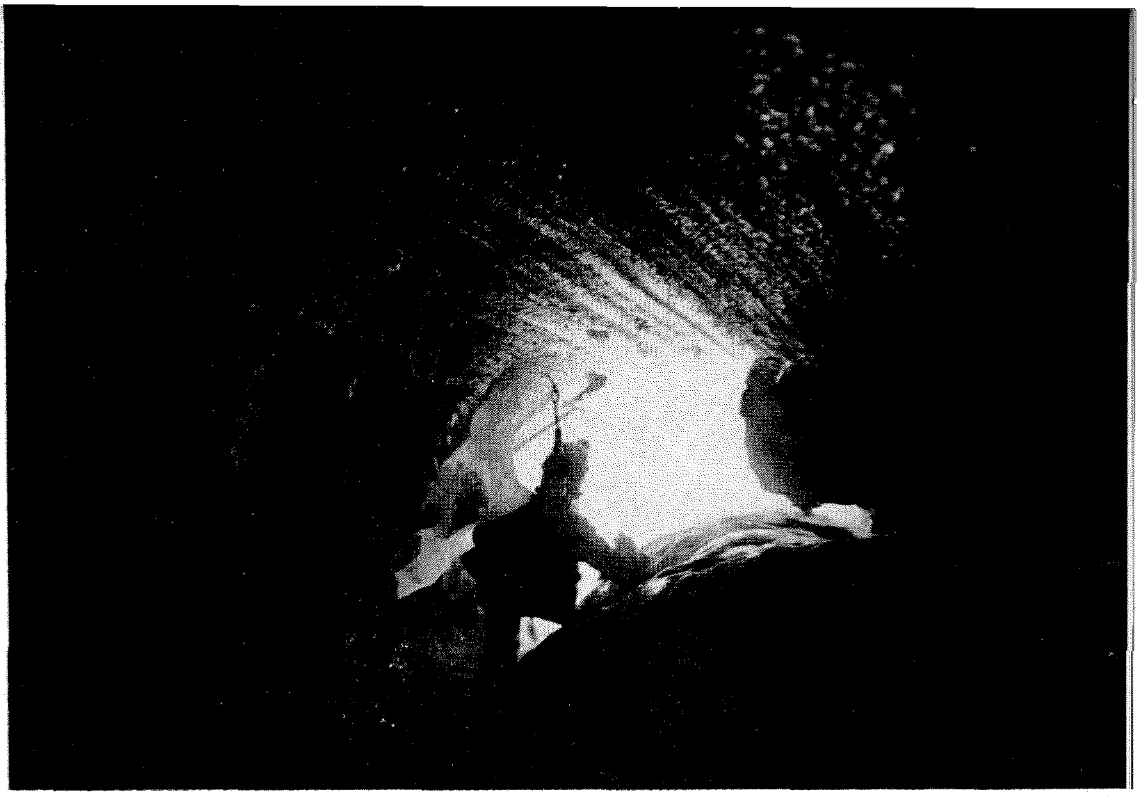
As we approached the bottom of the glacier the tunnel (below) began to squeeze shut rapidly under the pressure of the overlying ice; the walls were closing in as much as two or three centimeters overnight. This made completion of the tunnel to bedrock difficult because a large proportion of the digging effort had to expended just to keep the passageway open. On a hint from the borehole measurements, we excavated the tunnel in the shape of a Y, so as to reach bedrock at two places. We found that flow conditions at the two places, only about 15 m apart, were vastly different.

At the tip of one arm of the Y, the ice was separated from bedrock over wide areas, forming impressive caverns roofed by the grooved and striated

Two views of the glacier tunnel. At the left is the tunnel as it was originally excavated. At the right is a deeper part of the tunnel after some closure has occurred; the originally vertical walls have begun to bulge in and a "crease" has developed at the ceiling corners. By the time this picture was taken, the still deeper part of the tunnel—in the darkness up ahead—had closed in completely due to the overburden pressure.







The bottom of the glacier, as encountered at the head of the first branch of the tunnel. The picture is taken from inside a large subglacial cavern, and the roof overhead is the sole of the moving ice mass. The bright area is where the cavern is penetrated by the tunnel. You are looking down along the flow direction of the ice, as shown by the grooving of the sole.

sole of the moving ice mass (above). Here the sliding velocity was 35 cm per day, and most of the motion observed at the glacier surface was the direct result of this sliding. At the tip of the other arm of the Y, in contrast, the ice was in almost complete contact with the bedrock, and the sliding velocity was only 1 cm per day. In this arm of the tunnel the glacier motion was accommodated instead by very large plastic deformation rates within the ice, in a zone about 10 m thick at the bottom. Where this zone was penetrated by our boreholes, the holes tilted by more than 25 degrees in a two-week period, as a consequence of the ice deformation. When we consider that in large glaciers the maximum tilts are commonly only about 25 degrees *in a whole year*, we can appreciate how unusually large the shear strain rates observed here are. They are about 6 percent per day, an order of magnitude larger than ever measured in a glacier before.

We have not yet fully evaluated the implications of these observations, but a general conclusion stands out. Heretofore, we have tended to think of glacier motions as being fairly smooth, simple, one-valued functions of the driving forces or stresses, because we have tended to think of the motion-controlling mechanisms as being well defined by the pertinent stress variables. But in the present instance we see that the whole style and mechanism of flow can vary enormously from place to place near the glacier bed, in response to seemingly minor differences in conditions there. There appears to be a kind of instability in the controlling mechanisms for the over-all motion. On one hand, the ice may conform well to the bedrock, the shear stresses are large, and large plastic strain rates within the ice are responsible for most of the motion. On the other hand, with a relatively slight change in conditions, the ice may separate extensively from the bedrock, the shear stresses are widely relaxed, and a large sliding rate of the ice mass over bedrock occurs.

The situation may arise, I suspect, where this instability leads to a spreading out of the areas of extensive ice separation over a large part of the glacier bed, resulting in a great acceleration of the ice motion. I surmise that this is what happens in the hitherto unexplained catastrophic advances shown by some glaciers, notably in Alaska (the "galloping glaciers"), where motions of as large as 50 or even 100 meters per day sometimes occur.

These thoughts about complex natural phenomena, involving the combined action of many different physical forces and responses, seem to take us a long way from the basic and straightforward concerns about molecular structure of forms of ice and about forces of interaction between individual water molecules. Yet we hope ultimately to understand the natural phenomena of glacier flow in just such basic structural terms. Only in such terms could our understanding be adequate to extrapolate ideas from the world of ice to other worlds, such as the solid earth of silicate minerals below. And while striving for this understanding, we shall also, I hope, come to understand better the substance H_2O as a whole, in all its aspects—a substance that is, after all, one of the most important on our planet.

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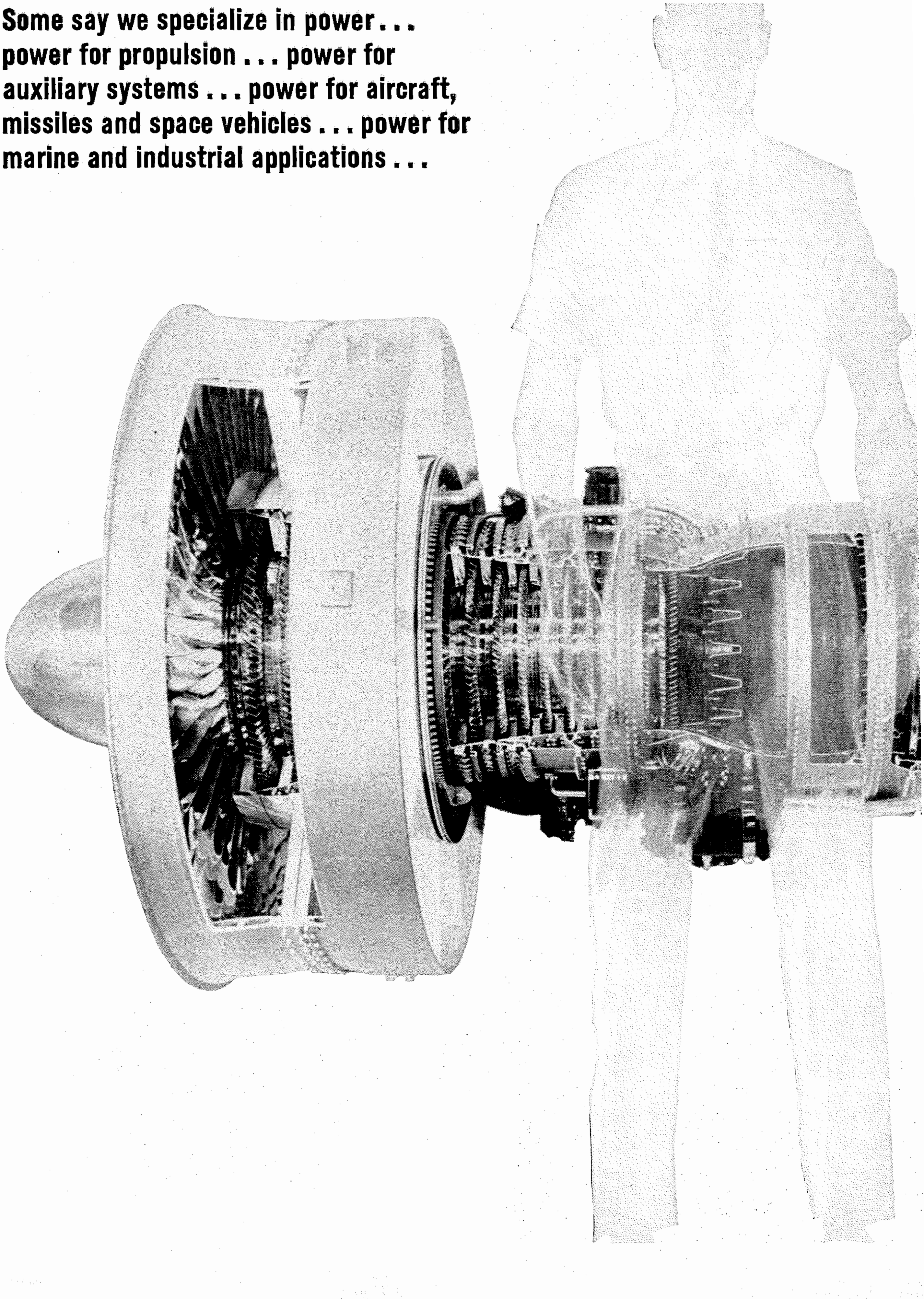
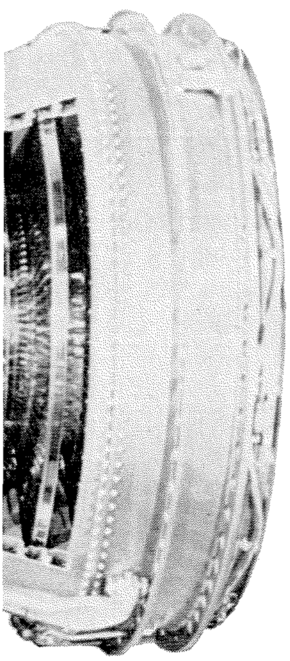


. . . they're right. And wrong.



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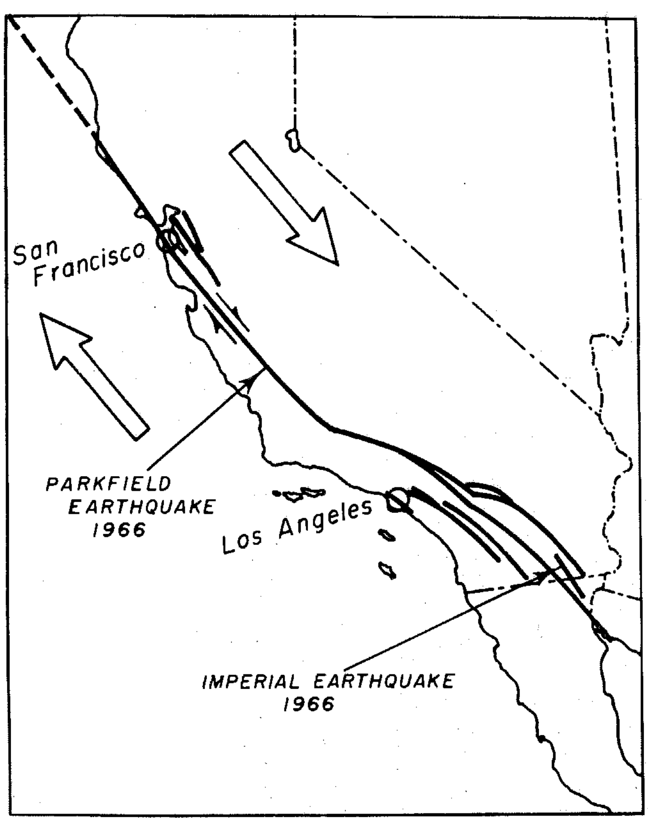
The Fault Slips

by James N. Brune

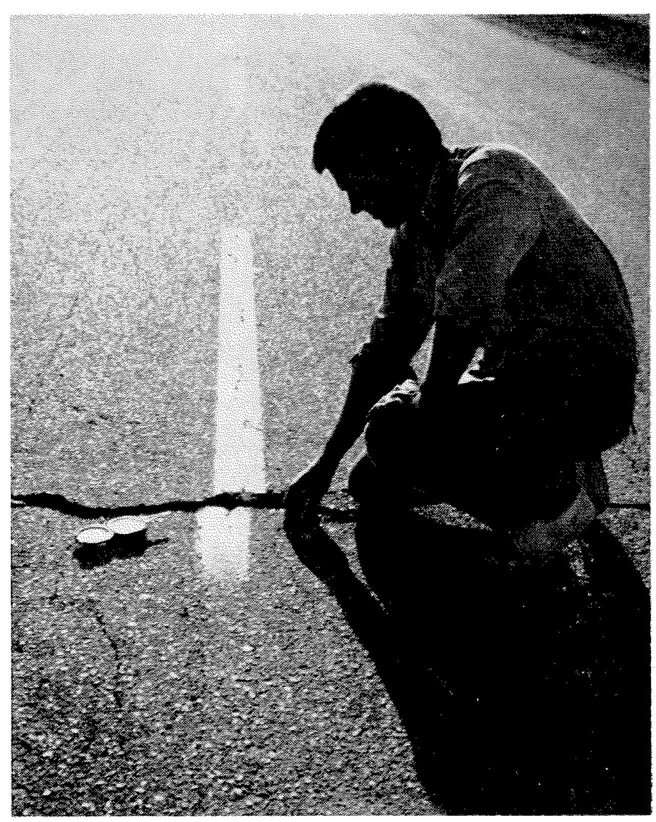
The ground convulses, buildings are twisted, statues and dishes are toppled, destructive waves are generated in oceans and bays, people panic. These are effects familiar to those who have experienced a large earthquake.

Small earthquakes, much more common than large ones, may also exhibit remarkable effects. Two recent earthquakes along the San Andreas fault (below) have pointed this out, much to the surprise of most of us in seismology. The Parkfield earthquake of June 27, 1966, magnitude 5.6, ruptured the ground for a distance of some 50 km and offset the white line on Highway 46 several centimeters. The Imperial earthquake of March 4, 1966, magnitude 3.6, offset the white line on Highway 80 about 1 cm and ruptured the ground for a distance of 10 km. This is the smallest earthquake yet known to be associated with ground breakage at the surface.

For centuries scientists, laymen, and astrologers have pondered the cause of earthquakes. The ancient Japanese believed that Japan perched upon the back of an enormous fish whose movements caused violent shaking of the land. Many other picturesque legends were developed by the ancients to explain earthquakes. A scientific approach to the explanation of earthquakes has only come about in



Map of California shows the direction of crustal movement on each side of the San Andreas fault and the location of two recent earthquakes.



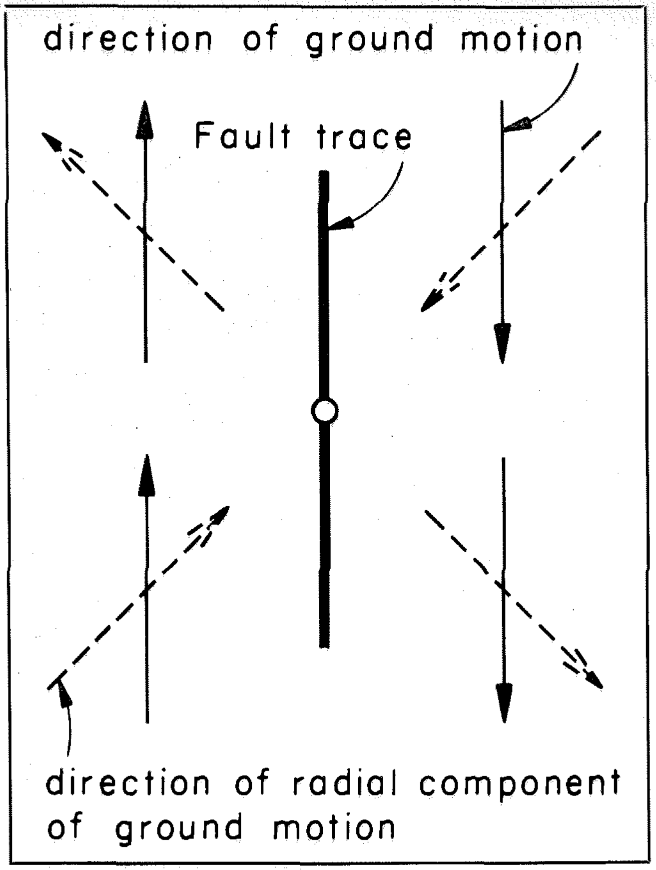
The white line on Highway 46 in central California was offset several centimeters as a result of the Parkfield earthquake of June 27, 1966.

the last century. The most impressive clue was the association of earthquakes with ruptures. For example, after the 1906 San Francisco earthquake the ground was found displaced as much as several meters along opposite sides of the San Andreas fault—the coastal side being moved to the north. This led Harry Fielding Reid to propose the elastic rebound theory of earthquakes. He suggested that strains are continuously being built up in the crust of the earth by subterranean forces of an unspecified nature. When the stresses in the rock reach the failing point, the rock breaks and slips along a plane determined by the shear stress and strength of the rock. The energy thus released propagates away from the source in the form of violent waves in the earth. These waves decrease rapidly in amplitude with increasing distance, but still may be recorded by seismographs at the most distant parts of the earth.

The elastic rebound theory has won general acceptance. It is an example of a phenomenon often observed in nature—rupture as a result of increasing strain. It explains (right) the quadrapole symmetry of first motion of compressional waves from earthquakes (i.e., in two opposing quadrants the radial component of initial motion is away from the center of the fault, and in the other two opposing quadrants it is toward the center). Other theories have been suggested for earthquake mechansim (e.g., explosive volcanic action or explosive change of state), but they have failed to explain the predominantly quadrapole distribution of first motions.

The origin of the forces that strain the crust of the earth has remained uncertain, but most recent evidence seems to suggest huge but very slow mass flow in the outer few hundred kilometers of the earth. Thus, the two sides of the San Andreas fault are driven by opposing mass flows. The pressure of the weight of the rocks keeps the sides of the fault together; when the stress reaches a critical value the fault breaks, causing an earthquake. In this simplified picture earthquakes along the San Andreas are equivalent to a large-scale chattering of two contacting frictional surfaces sheared relative to one another. Larger earthquakes occur when more energy is stored before slippage. If a long section of the fault is locked for a great length of time, energy for a very large earthquake may be stored up.

It has recently been possible to examine quantitatively the energetics of this process. Geodetic measurements carried on for many years have given us a reasonable idea of the long-term rate of motion. For example, in the Imperial Valley the observed northerly motion of the west side of the valley relative to the east side is observed to be about



The elastic rebound theory of earthquakes explains the fact that in two opposing quadrants the radial component of initial motion is away from the center of the fault, and in the other two opposing quadrants it is toward the center.

8 cm/year. About 5 cm/year is observed in central California near Hollister. Similar rates have also been inferred for spreading of the ocean floor away from the mid-ocean ridges.

If we were to observe the same rate of slip along a single crack striking through the center of a particular area, we might conclude that the fault is not locked and that energy is not being stored for a large earthquake. The actual situation is more complicated in most areas. For example, in the Imperial Valley, where there are numerous parallel faults, it is necessary to determine the amount of slip represented by the many small and moderate-sized earthquakes, most of which do not break to the surface.

Caltech's Seismological Laboratory has recorded earthquakes of magnitude greater than 3.0 in the Imperial Valley region for more than 30 years. From these data we may estimate whether the observed rate of occurrence of earthquakes is consistent with the rate of movement observed geodetically. For this purpose we use values of seismic moment, M_0, that represent the amount of torque or twisting of the ground occurring during an earthquake; it is directly proportional to the amplitude of seismic waves. To infer the rate of slip from the rate of occurrence of earthquakes we use the following equation relating moment to the average slip, $\bar{u}$, the rigidity, μ, and area of the fault surface, A: $\bar{u} = M_0/\mu A$.

To average this slip over the total cross-sectional area, A_0, we multiply by the area fraction A/A_0. The averaged slip, $\bar{\bar{u}}$, is thus given by:

$$\bar{\bar{u}} = \bar{u}\, A/A_0 = M_0/\mu A_0.$$

The sum over all events corresponds to the displacement of the two sides of the sheared zone resulting from earthquakes.

It is immediately noticed in the table below that even though the number of events increases as the magnitude decreases, the total contribution to the energy release and moment is very small for the smaller shocks. Thus, small shocks do not serve as a "safety valve" for larger shocks.

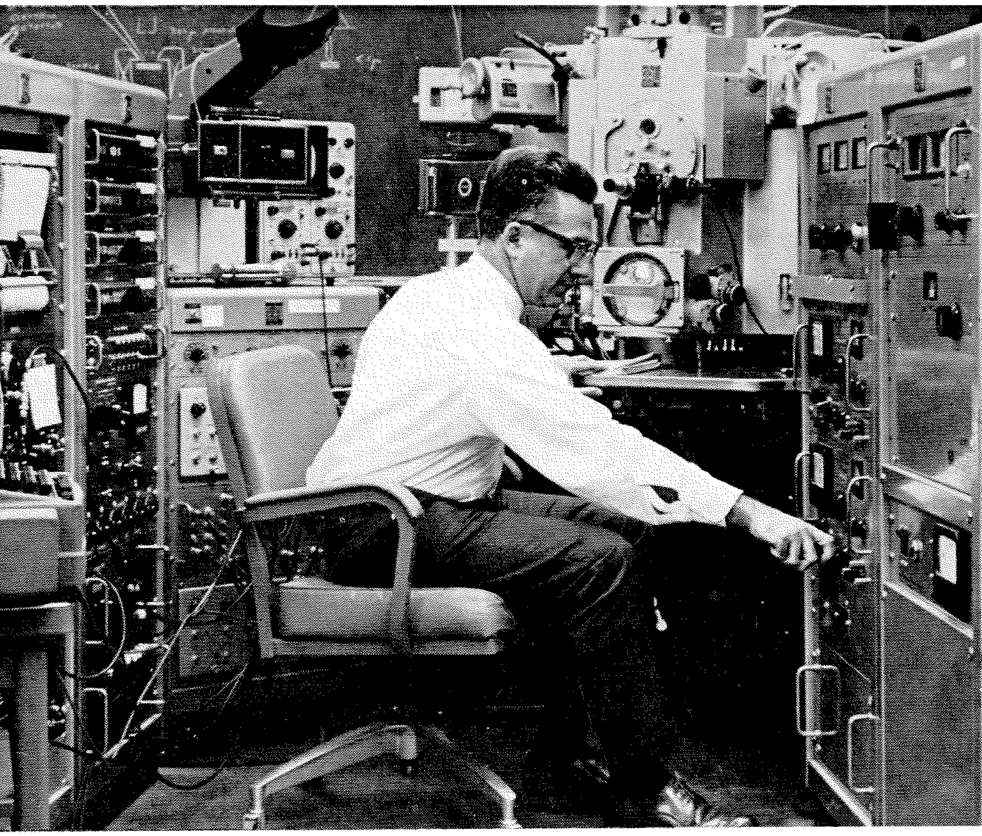
To calculate the slip represented by the total moment we must determine A_0, the cross-sectional area of the shear zone. For this we assume the depth of slippage to be 20 km, the approximate depth limit for earthquakes in California. The length of the shear zone is 120 km, making A_0 equal to 2.4 x 10^{13}cm^2. The calculated slip, 93 cm in 29 years, or about 3 cm/year, is less than half the geodetically observed rate of 8 cm/year of movement of one side of the valley relative to the other. This suggests either that stress (or potential slip) is accumulating at the rate of 5 cm/year or that a great deal of energy is being released by creep without causing earthquakes. Because of the probable existence of a large amount of undetected creep, we cannot be sure when sufficient strain for a large earthquake will have accumulated.

For the central section of the San Andreas fault between San Bernardino and the central coast ranges we may estimate somewhat more confidently the potential for a large earthquake, since here the fault consists of a single narrow zone. Essentially no earthquakes and no creep are observed along the fault at the present time, and we infer that the fault is locked and storing up energy. It may have been locked since about the time of the 1857 earthquake. If a rate of slip of 6 cm/year has occurred both north and south of this section since 1857, there is now a potential for an earthquake slip of about 7 meters, which would cause a great earthquake if released as a single event. The possibility that this energy could be released by some other mechanism (e.g., rapid creep or a series of moderate earthquakes) is remote.

To verify the ideas discussed here, it is important to measure the in-situ stress state of the rocks and thus determine directly the amount of energy available for an earthquake. Caltech is now testing several possibilities for making these very difficult measurements. It is believed that they offer the greatest hope for eventual prediction of the time and place of large earthquakes.

EARTHQUAKE SLIP IN THE IMPERIAL VALLEY, 1934-1963

Magnitude M	Energy E (ergs)	Moment M_0 (dyne-cm)	Number N	N-E (ergs)	N-M_0 (dyne-cm)
7.1	2.8 x 10^{22}	2.8 x 10^{26}	1	2.8 x 10^{22}	2.8 x 10^{26}
6 3/4	8.4 x 10^{21}	8.9 x 10^{25}	1	8.4 x 10^{21}	8.9 x 10^{25}
6 1/4	1.5 x 10^{21}	2.8 x 10^{25}	1	1.5 x 10^{21}	2.8 x 10^{25}
5 3/4	2.7 x 10^{20}	8.9 x 10^{24}	9	2.4 x 10^{21}	8.0 x 10^{25}
5 1/4	4.7 x 10^{19}	2.8 x 10^{24}	18	8.5 x 10^{20}	5.1 x 10^{25}
4 3/4	8.4 x 10^{18}	8.9 x 10^{23}	55	4.6 x 10^{20}	4.9 x 10^{25}
4 1/4	1.5 x 10^{18}	2.8 x 10^{23}	131	2.0 x 10^{20}	3.7 x 10^{25}
3 3/4	2.7 x 10^{17}	8.9 x 10^{22}	354	9.4 x 10^{19}	3.2 x 10^{25}
3 1/4	4.7 x 10^{16}	2.8 x 10^{22}	885	4.2 x 10^{19}	2.5 x 10^{25}
2 3/4	8.4 x 10^{15}	8.9 x 10^{21}	2212	1.9 x 10^{19}	2.0 x 10^{25}
2 1/4	1.5 x 10^{15}	2.8 x 10^{21}	5530	8.3 x 10^{18}	1.6 x 10^{25}
1 3/4	2.7 x 10^{14}	8.9 x 10^{20}	13825	3.7 x 10^{18}	1.2 x 10^{25}
1 1/4	4.7 x 10^{13}	2.8 x 10^{20}	34562	1.6 x 10^{18}	9.8 x 10^{24}
3/4	8.4 x 10^{12}	8.9 x 10^{19}	86405	7.3 x 10^{17}	7.7 x 10^{24}
1/4	1.5 x 10^{12}	2.8 x 10^{19}	21602	3.2 x 10^{17}	6.1 x 10^{24}
			Total E,M_0	4.2 x 10^{22}	7.4 x 10^{26}



The electron microprobe x-ray analyzer in Caltech's Division of Geological Sciences and its guardian angel, A. A. Chodos.

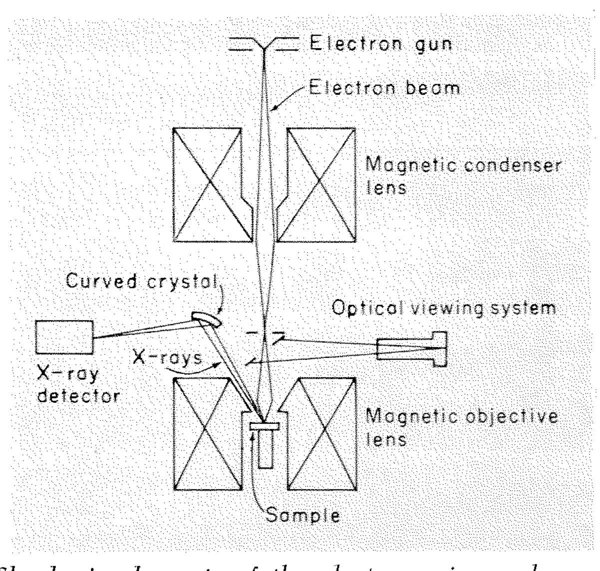
ROCKS — MICRON BY MICRON

by Arden L. Albee

The electron microprobe x-ray analyzer (the microprobe)—like the x-ray diffractometer, the emission spectrograph, and the mass spectrometer before it—is greatly changing petrologic and mineralogic investigation. With this instrument it is possible to make an accurate elemental analysis on a one-micron (0.001 mm) spot on a polished surface while simultaneously viewing the spot under a high-powered petrographic microscope. This makes it possible to correlate chemical composition with such physical properties of a mineral as zonal structure, grain boundaries, exsolution lamellae, or small inclusions.

The basic principle has been known for a long time and is, in fact, the basis for the x-ray tube. When a sample is bombarded by high-energy electrons, x-rays are excited in the sample with wavelengths characteristic of the various elements and with intensities, to a first approximation, proportional to the amount of the various elements in the sample. In the electron microprobe an electron beam is focused by magnetic lenses onto a polished surface of the sample to be analyzed.

The x-ray spectra produced are analyzed for wavelength by diffraction in a curved-crystal spectrometer and for intensity by a detector system. Analysis is carried out by comparing the intensity



The basic elements of the electron microprobe x-ray analyzer shown in schematic form.

of a characteristic wavelength of an element in the sample with the intensity of the same wavelength produced in a standard with a known concentration of the element. A spot, or a row of spots in a profile, may be analyzed simultaneously for several elements on different crystal-detector systems, or an area of the sample may be analyzed for a single element by systematic deflection of the beam as in a television tube. In addition, a single spot may be analyzed for many elements by scanning a range of wavelengths with the crystal-detector system and recording x-ray intensity versus wavelength.

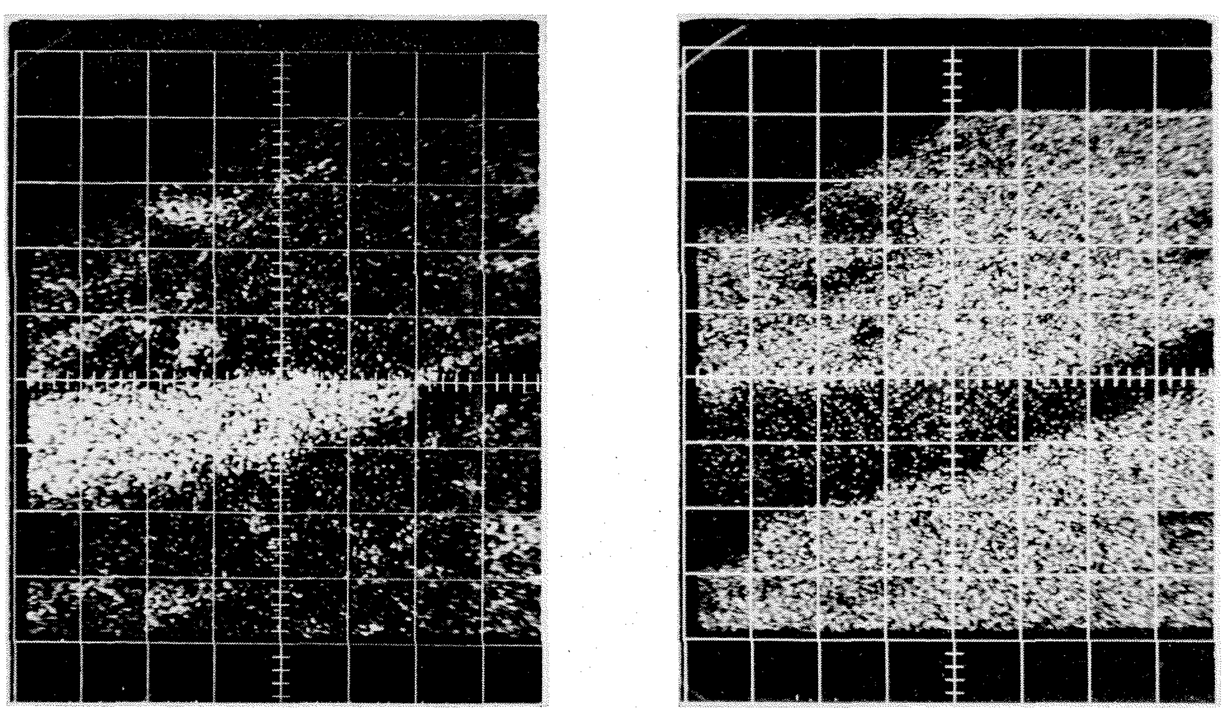
Caltech's microprobe is an Applied Research Laboratories EMX model, owned by the Jet Propulsion Laboratory and maintained and operated by A. A. Chodos of the geology division. Actual operation of the instrument is relatively simple, and it is used by graduate students and faculty alike in a wide variety of petrologic and mineralogic problems. Although a number of interesting problems have been undertaken for JPL, I can best indicate the usefulness of the instrument by describing some of the problems which have been undertaken by members of the division.

COMPOSITION OF COEXISTENT MINERALS

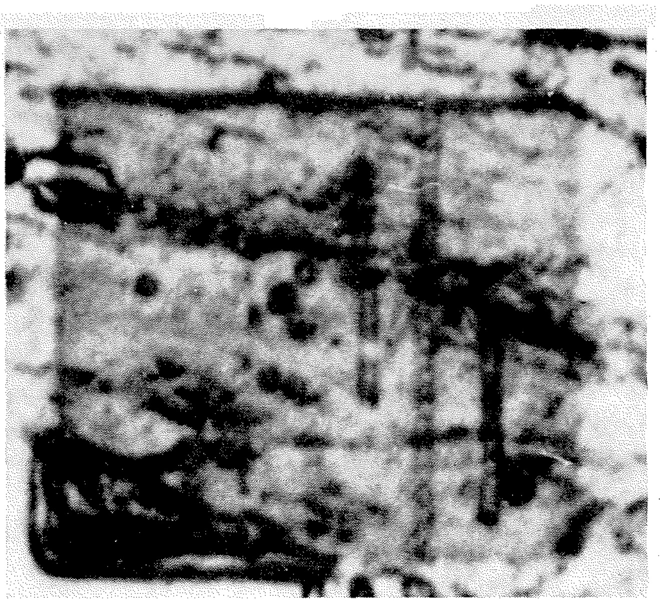
The chemical compositions of coexistent minerals in a rock are used by petrologists and geochemists to deduce the conditions under which the rock formed. Basically this is because a given array of atoms tends to aggregate into the configuration of lowest free energy for a given set of conditions. Hence an element (or an isotope) in a rock tends to be systematically partitioned between the mineral phases present, and the partition can be correlated with the conditions of formation, especially temperature. In the past such partition studies have required the mechanical separation of sufficient quantities of each mineral for chemical analyses, but truly pure separates of the phases are nearly impossible to attain. With the use of the microprobe, analyses are carried out in polished thin section on adjacent grains of the coexistent minerals; no mineral separation is required, and tiny inclusions of other minerals can be avoided.

A good example is provided by a study which has been made on muscovite, $[KAl_2(AlSi_3O_{10})(OH)_2]$ and its sodium analog, paragonite $[NaAl_2(AlSi_3O_{10})(OH)_2]$. The optical properties of these micas are so similar that they cannot be distinguished under the microscope, but x-ray diffraction studies had shown that the two commonly occur together. Although experimental work had provided information on the temperature dependency of their compositions, the similarity of all their physical properties had made separation for chemical analyses impossible.

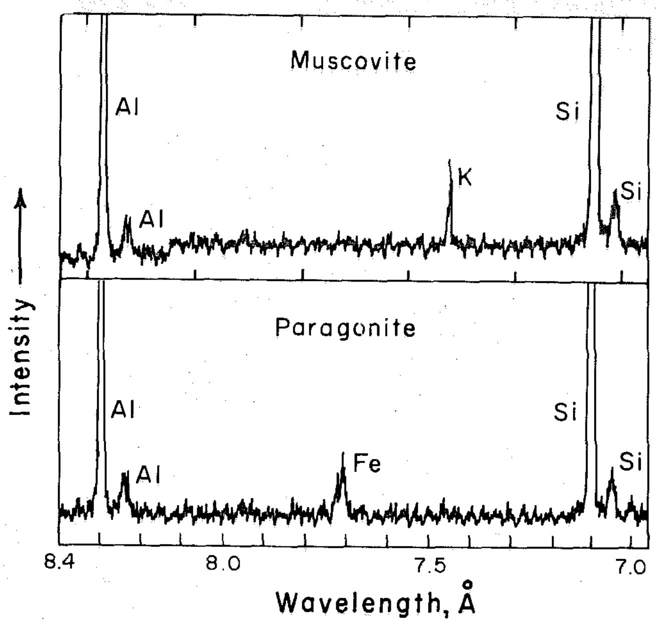
In the electron beam scans (below) for K and Na in a single grain of finely intergrown muscovite and paragonite, the density of white spots is proportional to the concentration of the analyzed element. The inverse relationship between the concentration of K and of Na is evident and corresponds to a wedge-shaped boundary visible in the photomicro-



In the electron beam scans for K (left) and Na (right), the density of white spots is proportional to their concentration. The area shown, 85 microns on a side, is the same as the shaded area in the photomicrograph on the opposite page.



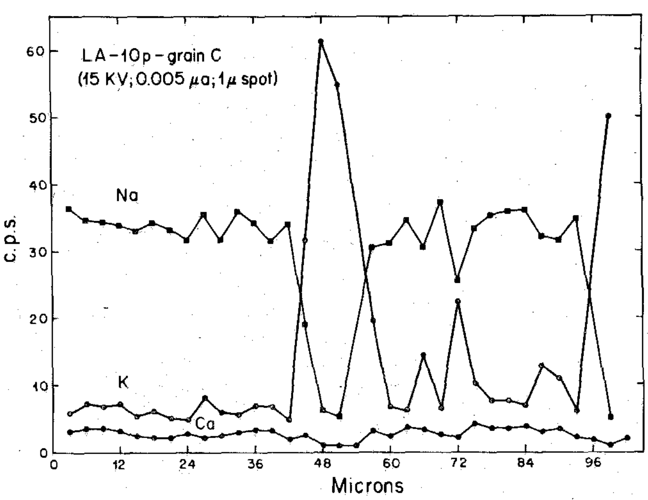
Photomicrograph of muscovite-paragonite grain.



These portions of wavelength scans for muscovite and paragonite show how the intensities of the K and Fe peaks differ in the two minerals.

graph of the grain (above). A simultaneous analysis for K, Na, and Ca in a profile of spots (taken along the long linear mark across the grain in the photomicrograph) is shown below. Another mode of analysis is a chart giving the x-ray intensity for each wavelength; such a chart (above right) shows a portion of a wavelength scan for a point in the muscovite and a point in the paragonite portion of the grain in the photomicrograph.

The muscovite and paragonite were analyzed to a greater accuracy by accumulating counts for a longer time at two points about 15 microns apart. These analyses correspond to the following formulas: Muscovite, $[K_{.77}Na_{.14}Ca_{.00}]\,[Al_{1.78}Fe_{.09}Mg_{.12}]\,[Al_{.84}Si_{3.16}O_{10}]\,[OH]_{1.98}$; Paragonite, $[K_{.07}Na_{.89}Ca_{.02}]\,[Al_{1.97}Fe_{.02}Mg_{.01}]\,[Al_{1.00}Si_{3.00}O_{10}]\,[OH]_{2.02}$. Plotting of the compositions of the coexistent muscovite and paragonite on a graph showing the temperatures at which muscovite and paragonite of a given composition were synthesized indicates that this metamorphic rock crystallized at a temperature somewhat above 500°C.

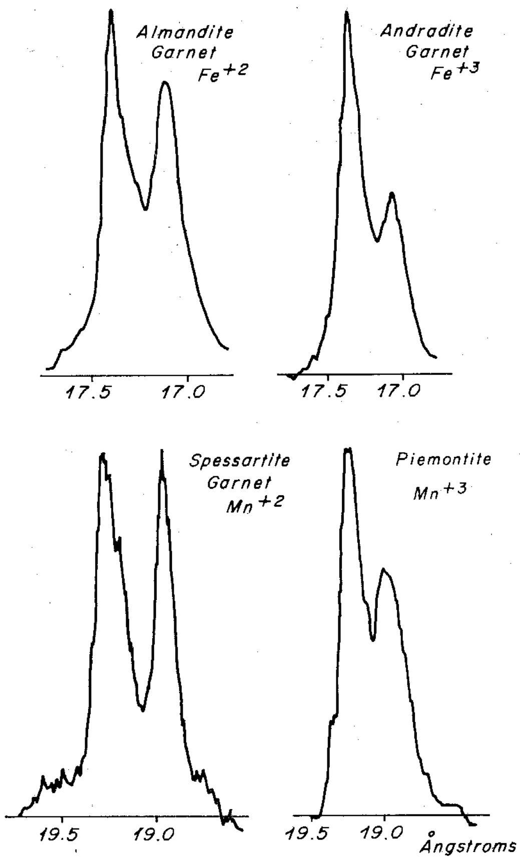


Simultaneous analyses for K, Na, and Ca in a profile across the grain shown in the above photomicrograph.

Similar investigations have shown that the minerals in many metamorphic rocks grew in chemical equilibrium with one another, since each of the elements is systematically partitioned between all of the phases present. Some elements, however, occur almost exclusively in a single mineral in the rock, suggesting that the crystal structure of that mineral has a nearly unique attraction for that element. For example, in garnet-bearing metamorphic rocks almost all the Mn^{+2} in the rock is in garnet.

VALENCE STATE OF IRON AND MANGANESE

The x-rays produced in the sample are emitted as electrons drop from an outer shell of the atom into an inner shell. Since Fe and Mn in different valence states have different numbers and configurations of electrons in their outer shell, the wavelengths and intensities of the emitted x-rays vary slightly with the valence state. The variations can be seen in portions of wavelength scans for different minerals high in Fe^{+2}, Fe^{+3}, Mn^{+2}, or Mn^{+3}. Both the wavelength and the $L\beta/L\alpha$ intensity ratio varies with the valence state. These relationships were developed during an investigation of interlayered green and red gneisses. The green coloring is due to abundant epidote $[Ca_3(Al, Fe^{+3})_2(SiO_4)_3(OH)]$, and the red coloring is due to abundant piemontite, which has the same crystal structure but which contains manganese. The analyses verified that the red color of piemontite is due to highly oxidizing con-



Portions of wavelength scans showing $L\beta/L\alpha$ *intensity for different minerals high in* Fe^{+2}, Fe^{+3}, Mn^{+2}, or Mn^{+3}.

ditions resulting in the presence of Mn^{+3}, rather than simply due to a high manganese content.

COMPOSITIONAL ZONING IN MINERALS

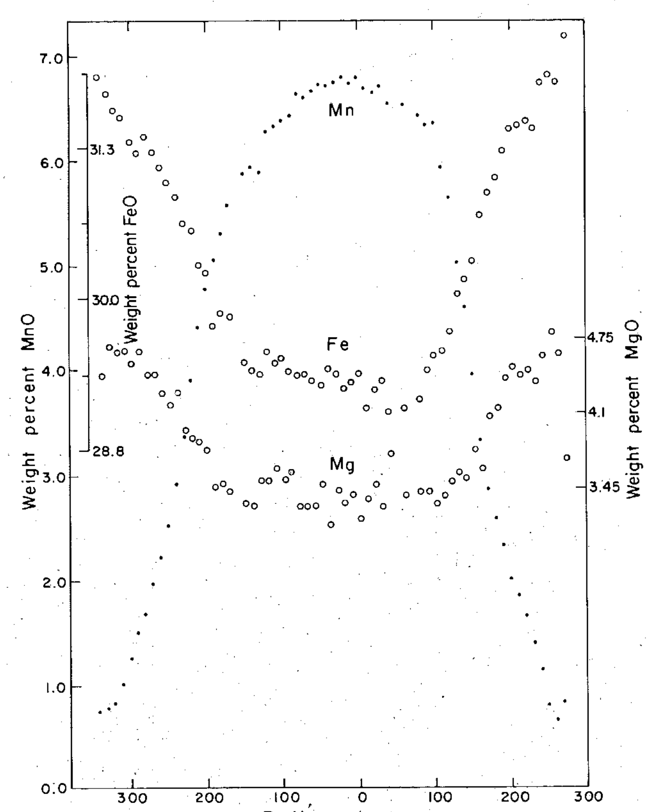
Some of the most interesting microprobe results are from studies of zoned minerals, since these give us information on the mineral growth history that can be obtained in no other way.

Garnet is a very common mineral in metamorphic rocks; it has a wide range of chemical composition expressed by its formula: $(Fe^{+2},Mg,Mn,Ca)_3(Al,Fe^{+3})_2(SiO_4)_3$. As indicated earlier, it has a very strong attraction for Mn^{+2}, and it has long been known that the garnet in low-grade metamorphic rocks is commonly highly manganiferous. Microprobe analyses have shown that garnet is almost invariably extensively zoned, typically with the pattern for Mn-variations shown at the right. The zoning indicates that, as the garnet crystal grew, each layer mantled the interior so that it did not equilibrate with the other minerals in the rock. This zoning pattern can be reproduced by a calculated model which assumes that Mn^{+2} is strongly partitioned into garnet, that each layer as it grows takes up a constant high proportion of the remaining Mn^{+2} in the rock, and that the amount of remaining Mn^{+2} is constantly depleted by the growth of the garnet. In some cases perturbations on this pattern can be related to variation in temperature or other conditions during the growth of the garnet.

OTHER STUDIES

Other studies that have been undertaken include the development of correction parameters which make possible the accurate analysis of complex silicates using simple silicates and oxides as standards. The homogeneity of the zircons used in age dating and the possible implications of their zoning have also been investigated. Microprobe analyses have been used in studies of the detailed crystallization history of a porphyry stock in the Death Valley region and of a layered diabase in Arizona. Coexisting minerals from an explosive peridotite pipe in northern Arizona have been analyzed, since such pipes may be derived from very deep within or below the earth's crust. Silicate inclusions in iron meteorites have been analyzed and identified by the microprobe. The chemical and mineralogic composition of the small teeth of chitons have been investigated. Analyses of various parts of the shells of fossils are used to study the conditions of animal growth.

These are only a sampling of the types of problems to which the microprobe is currently being applied. Within a few years the special capabilities of the microprobe will make it indispensable in most petrologic and mineralogic investigation.



Profile showing typical composition variation across a single garnet crystal.

THE MANTLE OF THE EARTH

by Don L. Anderson

In the first decade of this century physicists discovered that the atom had a massive central core which they called a nucleus, and geophysicists discovered that the earth had a massive central nucleus which they called a core. The study of the interior of the atom, the smallest building block of matter, and the study of the interior of the earth, the largest piece of matter to which man has direct access, have proceeded rapidly for the last 60 years. We now have exquisitely detailed information about the interior of both the atom and the earth.

Although the study of the atom and the study of the earth have proceeded independently, they are conceptually very similar, and advances in the one field often have direct and sometimes surprising pertinence to the other. In neither case can the interiors of the objects of study be observed directly. Their properties are deduced or inferred from physical effects. For example, the atomic nucleus was discovered by the scattering of electron beams; the earth's core was discovered by the scattering of seismic waves.

Advances in the understanding of matter have led to advances in our understanding of the composition and physical state of the earth's interior. The behavior of material at great depth in the earth is one of our best guides in the study of effects of high static pressure and high temperature on the properties of solids, a currently active branch of solid state physics and materials science .The anomalous behavior of the mantle at a depth of about 400 kilometers stimulated much research in the polymorphism of solids.

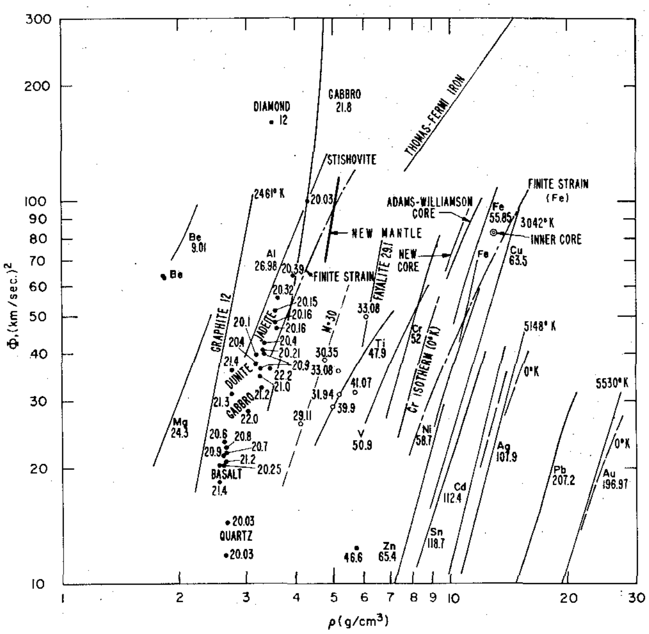
When atomic physicists were able to tap the energy of the nucleus, they made available to the geophysicist a seismic energy source much less temperamental and more predictable than earthquakes. For the first time the study of the earth could proceed as a controlled experiment. The ability of the geophysicist to detect and measure very small ground motions was an important part of the nuclear test ban negotiations and, in essence, made the geophysicist the watchdog of the progress of physics in other countries.

INFORMATION FROM SEISMIC WAVES

Earthquakes radiate elastic waves in all directions, and the time they take in travelling from the earthquake focus to various parts of the earth's surface is the basic information from which the structure of the earth's interior is inferred. Clearly, the location of the earthquake both in time and space must be known in order to infer the path of the seismic wave and the time it takes in its journey. However, the seismic waves themselves are the best source of information regarding the location and time of the earthquake. The accuracy of location depends on the accuracy with which the velocities in the earth are known. This seismic uncertainty principle is responsible for a certain fuzziness in our models of the earth's interior and in our maps of the distribution of earthquakes .

Earthquakes are not point sources in space or time. Furthermore, their occurrence in time and space cannot be predicted. The study of earthquakes and the use of earthquakes to study the earth therefore amounts to a continuous monitoring program. Neither earthquakes nor seismometers are uniformly distributed over the surface of the earth, so many years of monitoring are required to build up an adequate description of the earth's interior.

Buried nuclear explosions provide a quite satisfactory point source of seismic energy. Since nuclear tests are well located and well timed, they have been a boon to seismologists. With the ambiguities of the source removed, a more detailed picture of



A comparison of laboratory shock wave data for rocks and seismic data (where ϕ is the square of the hydrodynamic sound velocity and ρ is density) shows that the mantle has a mean atomic weight near 23 and that the core is slightly less dense than pure iron.

the earth can be drawn. The development of nuclear weapons has had other fallout for geophysics. No nuclear test ban treaty can be effective unless underground tests in other countries can be monitored. This monitoring requires the installation of very sensitive seismometer networks in many parts of the world. The more seismometers that are operating, the more accurately can natural events— as well as artificial explosions— be located, and the more precise becomes our understanding of the structure and physical properties of the earth's interior. Thus the physicist's ability to split the atom has contributed substantially to the study of the earth's interior.

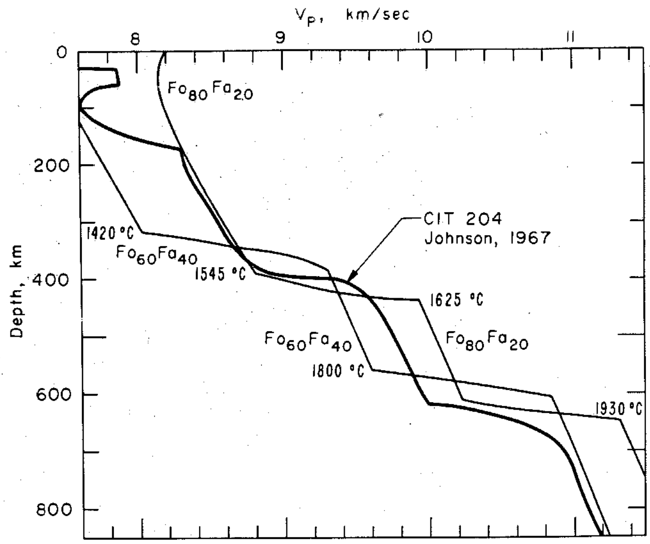
There is still a third area in which developments in atomic physics have had direct impact on geophysics. People who put nuclear devices in big holes in the ground like to know how the intense shock waves are affecting their "container." To answer this question they have supported shock wave research on rocks. During the passage of a shock wave the rock is exposed to extremely high pressures and temperatures and, in a well-controlled experiment, the physical properties of the rock under these extreme conditions can be measured. Pressures of the order of several megabars and temperatures of the order of thousands of degrees Kelvin can be routinely generated in these shock wave experiments which use shaped charges of conventional explosives.

Static high-pressure equipment using large presses can go up to about 100 kilobars, which is equivalent to only about 300 km deep in the earth or 1/20th of the way to the center. Measurements of the elastic properties of rocks have only been made up to about 15 kb, which corresponds to a depth not much below the crust of the earth. Since seismic experiments involve elastic properties throughout the earth, large extrapolations have been required to convert seismic data to standard conditions and, hence, discuss the composition and temperature of the interior. Geophysicists have therefore been concerned for some time both with theoretical equations of state which will allow them to compute the effects of temperature and pressure on the density and elastic constants of silicates and oxides and with the stability of complicated crystal lattices. Shock wave data on rocks can be compared fairly directly with data available from seismology, and we are now making rapid progress in our ability to infer the composition and physical state of the material at all depths in the earth's interior. By comparing the shock wave data with the seismic data (left) we can estimate the mean atomic weight of the mantle and core. We conclude that the mantle is a magnesium-rich silicate and that the core is probably iron mixed with some lighter material.

Unfortunately, shock waves supply only one elastic constant--the compressibility—and the effects of temperature can only be treated approximately. There is still considerable interest in the lower-pressure experiments and in theoretical equations of state. Silicates are structurally complicated, however, and the interatomic forces between constituent ions are not as clear-cut as in simple ionic crystals, so no one has carried out a complete lattice dynamical or quantum mechanical calculation for any common rock-forming mineral. Even pressures in the core are too low for applicability of simplified statistical treatments such as the Thomas-Fermi equation of state. Semi-empirical equations of state, such as the finite strain equations of Birch and Murnaghan, have therefore been widely used by geophysicists both to extrapolate low-pressure data and to indicate how ultrahigh-pressure equations of state must be modified to have the proper low-pressure behavior.

The major subdivisions of the earth's interior (determined from variations in the velocity with which compressional waves travel through the earth) are the crust, mantle, and core. Within these subdivisions, from the center out, there are the solid inner core, a transition region between inner and outer core, the liquid outer core, a transition region between the liquid core and the solid mantle, the lower mantle, a transition region which separates normal silicates from their high-pressure polymorphs, the upper mantle, and the crust.

The upper mantle varies locally and is different under oceans than it is under tectonic areas and stable continental shield areas. The graph at right gives the structure of the upper mantle and transition region in the western part of North America, a tectonic area. This structure resulted from a detailed study by Lane Johnson of the apparent velocities of seismic waves across the large crossed array in Arizona. This array was set up by the Air Force as part of the nuclear test detection program, and the data are routinely sent to Caltech's Seismological Laboratory.

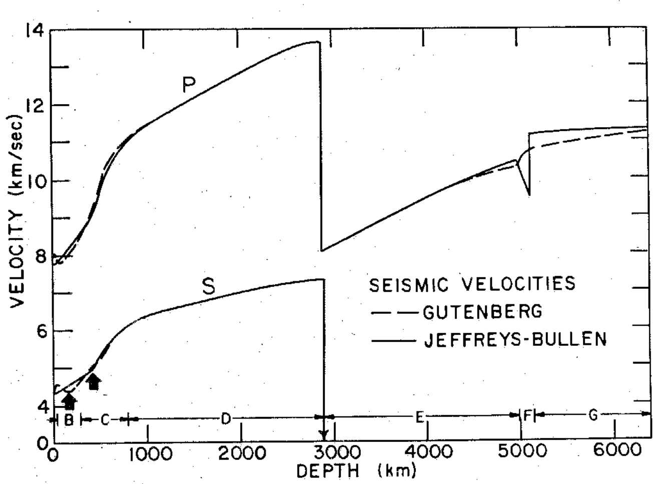


The structure of the upper mantle and transition region in western North America (heavy line) is compared with theoretical mantle models (light lines) that take into account temperature, pressure, and phase changes.

LOW-VELOCITY ZONE

We are not sure what causes the pronounced low-velocity zone at the 100 km depth; it may represent a different mineral assemblage than the adjacent regions of the mantle, or the material in this zone may be partially molten. It may also be caused by a particularly large thermal gradient in this region of the earth, a thermal gradient so large that the effects of pressure are completely cancelled out.

The low-velocity zone is also present in oceanic areas but is virtually absent in stable shield areas. Seismic waves, particularly shear waves, that penetrate this zone are attenuated very rapidly. In some volcanic regions shear waves cannot even get through this zone, suggesting that it is almost totally molten and is, in fact, the source of magma for the volcanos. In Hawaii some volcanic eruptions are preceded by earthquake activity in the low-velocity layer, which again suggests that this low-velocity layer is at least partially molten.



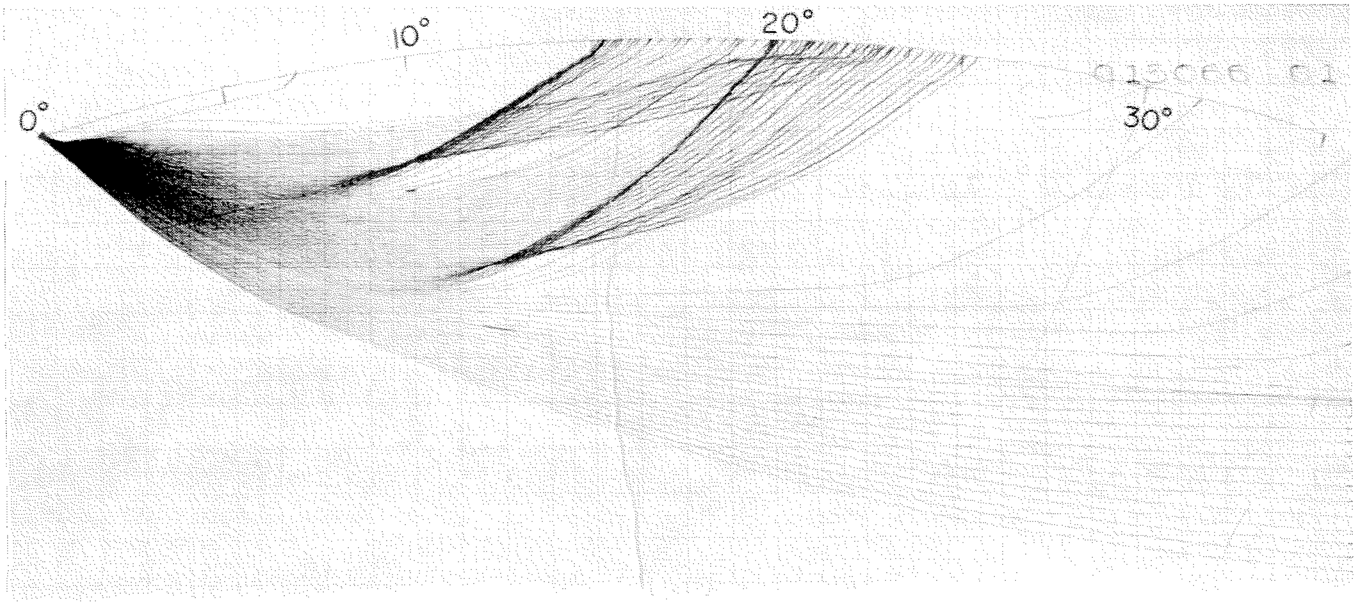
The major subdivisions of the earth's interior are determined from variations in the velocity of compression waves traveling through the earth: (B) upper mantle; (C) transition region; (D) lower mantle; (E) liquid outer core; (F) transition region; (G) solid outer core.

The low-velocity zone is terminated fairly abruptly at about 150 km, indicating a sudden change in the physical state or the composition of the material at this depth. The magnitude and abruptness of the velocity change argue for a compositional change. Perhaps the lighter fraction of the mantle, which also has a lower melting point, has migrated upward, leaving behind a refractory residue which not only has higher velocities but is further from its melting point.

The low-velocity zone may represent a great reservoir of magma held in a solid matrix, as water is held in a sponge. Since molten rock is enriched in radioactivity, a partially molten zone is self-perpetuating. The conductivity of rock is so low that internally generated heat is effectively held in the earth unless the molten rock is allowed to escape to the surface or to shallow depths. This apparently happens in zones of crustal weakness and results initially in lines of volcanos and ultimately in the formation of new crust.

The formation of continents may be due to the upper mantle turning itself inside out in this way. Stable regions of the earth's crust, such as the Canadian Shield, lack a low-velocity zone and apparently have long since depleted their underlying mantle of its magma and its radioactive source of internal heating, and are therefore quiescent.

Low densities are usually associated with low seismic velocities. If the trend in density is similar to the trend in velocity, then the upper mantle in oceanic and tectonic areas would be unstably stratified.



Plot of waves in the upper mantle radiating from a point source shows effect of refraction through various regions.

From about 150 to 400 km in depth the seismic velocities increase at the rate one would expect from the effects of self-compression. Near 400 km the velocity begins to increase very rapidly; this is the transition region. Seismic waves are bent very strongly when they go through such a region. Seismologists can only observe the wave when it finally reaches the surface of the earth, and it has taken them many years to untangle the spider web pattern of ray paths through the upper mantle (above).

Scientists at Caltech's Seismological Laboratory were unraveling the seismic rays in this transition region at the same time that important high-pressure measurements were being made in Japan and Australia. Scientists in these countries were subjecting olivine, a prime candidate for the main mineral of the upper mantle, to pressures of the order of 100 kb. Olivine has a very open-packed crystal structure, as do most common silicates, and it had been predicted that it would collapse under high pressure to a form approximately 10 percent denser. The high-pressure experiments verified this prediction and provided the information necessary to calculate the details of the transition. Furthermore, thermochemical data now made it possible to predict the pressure at which this new phase would collapse still further to an even denser high-pressure phase.

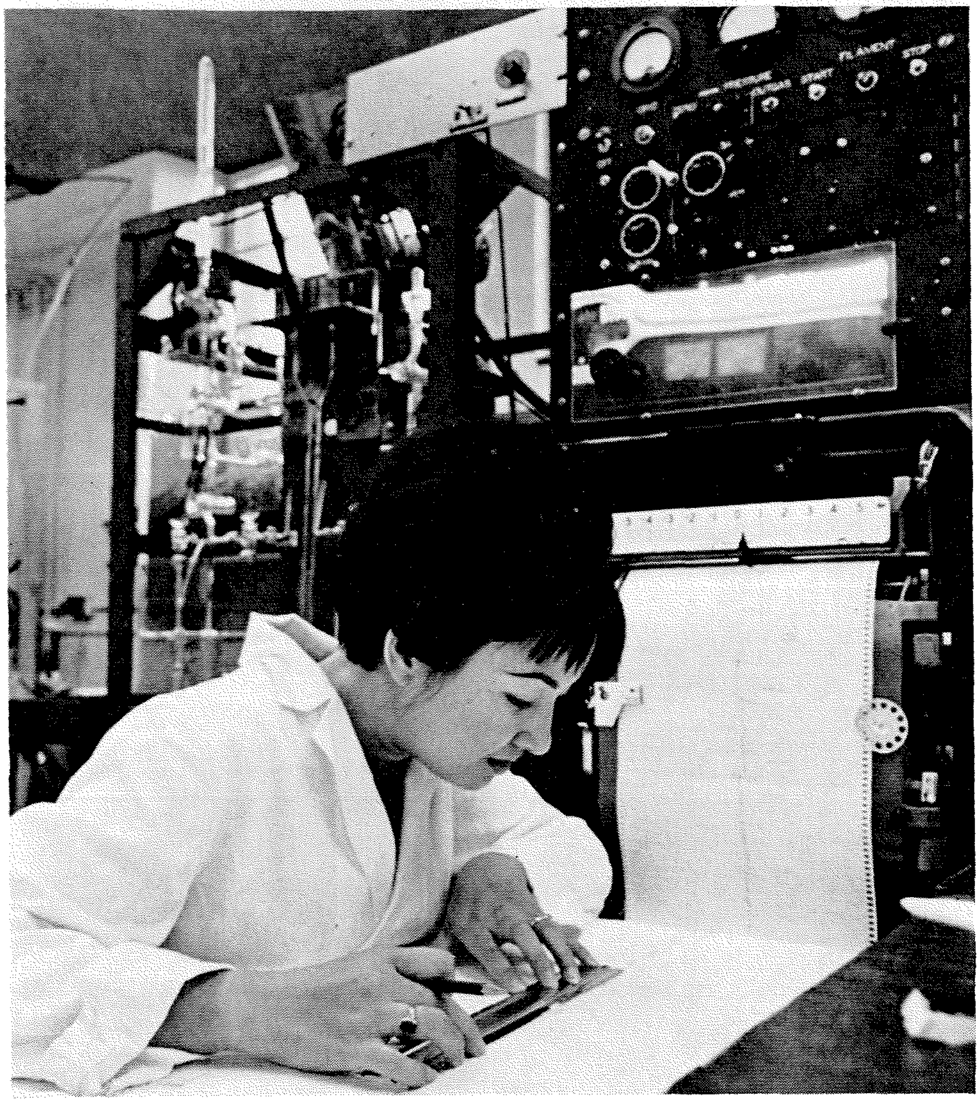
The depths at which these transformations occur depend on both the temperature and the composition of the olivine. Olivine occurs as pure forsterite (Mg_2SiO_4) and pure fayalite (Fe_2SiO_4), and all intermediate compositions are possible. Most olivines are magnesium-rich, and the olivine in the mantle is probably 60 to 80 percent forsterite (Fo_{60} Fa_{40} to F_{80} Fa_{20}). The remarkable similarity between these theoretical mantles and the new seismic results leaves little doubt that two successive phase changes are indeed taking place and that these phase changes dominate events in the transition region.

MORE QUESTIONS

The factors controlling the distribution of earthquakes have intrigued seismologists for many years. By far the greatest number of earthquakes occur in the crust. In some tectonic regions the distribution with depth approximates a decreasing exponential curve interrupted by small maxima near 80, 180, 350, and 600 km. The deepest known earthquake occurred near 700 km. Each one of these depths is near a prominent feature of the new velocity depth curve. No such correlation existed for previous mantle models.

The location of tectonic belts and great fracture and ridge systems suggests that the earth is subjected to some worldwide stress system. Are these stresses most effectively concentrated where the elastic properties are changing most rapidly? The ability of a solid to creep—its viscosity, if you will—seems to be well correlated with its elastic properties. Is the mismatch in ability of the earth to deform at various levels responsible for deep-focus earthquakes? Or is the mantle out of the thermodynamic equilibrium in tectonic regions, and do the phase changes themselves cause earthquakes? Or is it the readjustment of the earth to these phase changes that is the source of earthquakes?

As usual, the result of a scientific study generates as many questions as it answers.



Caltech technician using the light element gas mass spectrometer.

THE STABLE ISOTOPES

by Samuel Epstein

For the past 15 years the Division of Geological Sciences has had an active program in geochemistry dealing with studies of the natural variations of the isotopic abundances of some of the lighter elements. Such studies are of use to the geologist, geochemist, and other geoscientists in their studies of earth processes.

Most elements, as they exist in nature, are composed of non-radioactive isotopes. Isotopes of a single element have the same number of protons but a different number of neutrons in their nuclei. Chlorine consists of two stable isotopes of atomic weights 35 and 37. Calcium has six stable isotopes of atomic weights 40, 42, 43, 44, 46, and 48. The isotopes of an element are physically and chemically very similiar. In compounds, the chemical and physical properties of the different combinations of Ca and Cl isotopes—various isotopic species of calcium chloride—are also similar, and calcium chloride is customarily referred to as a single chemical and not as it really exists, a mixture of such isotopic species as $Ca^{40}Cl^{35}$, $Ca^{40}Cl^{37}$, $Ca^{42}Cl^{35}$, etc.

For most practical purposes such treatment of chemical compounds is proper. Most scientists, however, are aware that they are dealing with mixtures of isotopic species of compounds when they refer to, say, H_2O or NaCl, and that the isotopic species of a single compound are chemically and physically not identical. These differences in properties are particularly relevant in cases where the lighter elements are concerned. Pure H_2^2O is measurably different from H_2^1O. Its vapor pressure, at room temperature, is lower by some 7 percent than that of H_2^1O; its freezing point is 3.8°C higher.

The differences in chemical and physical properties of isotopic species of a chemical compound are due to the fact that the mass of an atom is a factor in the bond strengths of the atoms in a compound. Although the electronic configurations in O^{16} and O^{18} are the same, when O^{16} combines with hydrogen to form H_2O^{16} the bonds formed are less stable than the equivalent bonds in H_2O^{18}. Thus, when water is subjected to some processes, the H_2O^{16} will respond differently than will H_2O^{18}.

The process of freezing of water causes a decrease in the H_2O^{18} content in the unfrozen water because H_2O^{18} freezes preferentially relative to H_2O^{16}.

The differences in the chemical and physical properties of the isotopic species of a compound can be exploited to study a variety of processes and can be applied to many different problems. We can perhaps best illustrate the usefulness of isotopic studies by considering some investigations of the variations in the oxygen isotopic abundance, specifically with the O^{18}/O^{16} ratio in natural oxygen compounds.

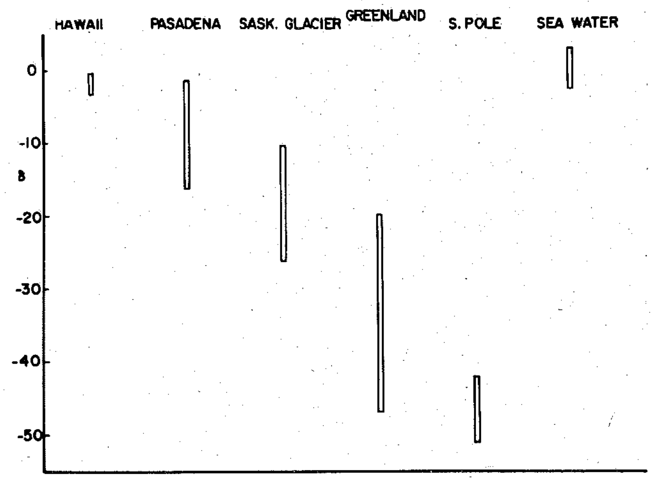
Measurements have been made of the O^{18}/O^{16} ratio in water and ice, in nearly all the common silicates, carbonates, and in a variety of oxides. These measurements, which must be made with high precision to be meaningful, were made possible by development of a mass spectrometer that can detect the addition of one O^{18} in 2×10^6 atoms of oxygen. In other words, a change of 0.01% in the O^{18}/O^{16} ratio (normally 1/500) can be measured routinely.

Variations in the O^{18}/O^{16} ratio are described in terms of delta values, where delta is the permil change of the O^{18}/O^{16} ratio relative to the O^{18}/O^{16} of a given standard. The standard is usually mean ocean water. Thus, an oxygen sample with a delta value of + 10 has an O^{18}/O^{16} ratio of 1 percent or 10 permil greater than that of mean ocean water. A delta value of -10 denotes a ratio of 1 percent or 10 permil lower than that of mean ocean water. We use this notation because we are interested primarily in how the various natural materials differ in the O^{18}/O^{16} ratio, rather than in the absolute value of the ratio.

O^{18}/O^{16} RATIOS AND WATER STUDIES

As an illustration of this isotopic effect, consider the implications of the fact that at room temperature the vapor pressure of H_2O^{16} is greater than that of H_2O^{18} by some 1 percent. The transfer of water in the meteorological cycle of the world is due to the processes of evaporation and condensation. If we keep in mind that, with each partial evaporation of a water body and with every partial condensation of water vapor in the atmosphere, there is an accompanying isotopic change in the resulting liquids and vapor, then we can readily understand that different rains, lakes, ocean waters, glaciers, and rivers have acquired an O^{18}/O^{16} ratio that is related to the detailed history of these waters in terms of the evaporation and condensation cycles.

The O^{18}/O^{16} ratios of the oceans are the least variable of these natural waters. Yet systematic differences in the isotopic composition of the oceans are measurable. Surface ocean waters in the warmer areas of the world are usually enriched in H_2O^{18} because these waters suffer evaporation and are the main source of water vapor for the atmosphere. The cold ocean surfaces in the northern and southern areas are usually slightly enriched in H_2O^{16} because there is a resultant addition of fresh waters from rains, snow, and continental runoff.



The range of the O^{18}/O^{16} ratios of precipitation at localities from different latitudes. The lengths of the bars represent about the maximum range in the δ values in the designated locality.

An additional factor governing the O^{18}/O^{16} ratio of the ocean waters is the O^{18}/O^{16} ratio of the fresh water which is added or depleted from the surface of the oceans. For example, an ocean water sample collected at a depth of about 7,500 meters near the equatorial regions in the Atlantic Ocean showed a relatively normal salinity value, yet its O^{18}/O^{16} ratio was somewhat lower than might be expected for deep ocean water.

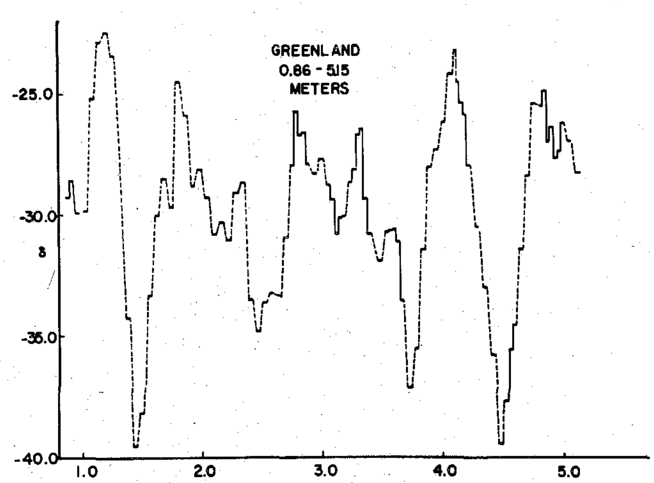
It was apparent that this sample could only have acquired its isotopic composition by being exposed to the surface at the polar areas and by receiving some melt water of unusually low O^{18}/O^{16} ratio and then becoming part of the sinking cold waters that reached as far as the equatorial latitudes.

In summary, the isotopic composition of the ocean water represents a natural label which permits the tracing of horizontal and vertical ocean currents. Since the understanding of the movements of ocean water is of concern to physical oceanographers, isotopic surveys of ocean currents are important to the field of oceanography.

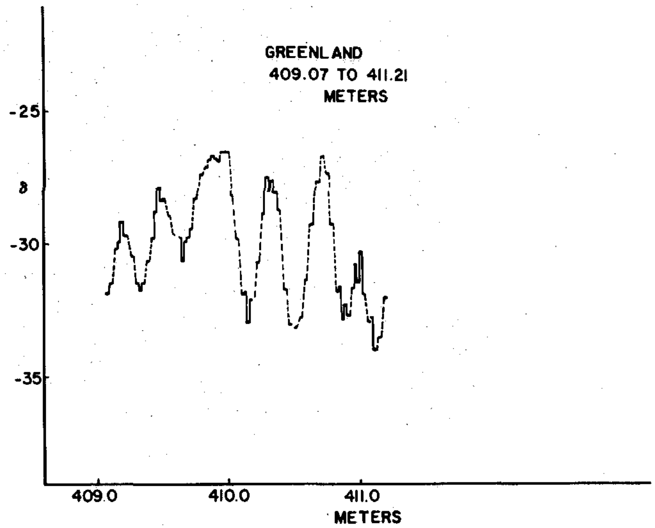
The isotopic compositions of water vapor in air masses and of precipitation are extremely variable, and are dependent upon the cooling and warming history of the air masses. Studies of the isotopic composition of water vapor in air samples and of the isotopic composition of rain and snow samples can give important and unique information about the movement of air masses and the history of moisture in the meteorological cycles. On a worldwide basis the O^{18}/O^{16} ratio of precipitation changes with latitude (left). Generally, the colder an area the less H_2O^{18} in the precipitation. In addition, the O^{18}/O^{16} ratio of precipitation falling on a single area such as Pasadena or Greenland displays a seasonal variation, and winter precipitation has less H_2O^{18} than summer precipitation. Because a mass of water vapor will preferentially lose H_2O^{18} during precipitation, a tropical air mass, as it cools on its complicated journey northwards, will continuously suffer preferntial loss of H_2O^{18}. By the time such an air mass reaches Greenland, it will have lost a large fraction of its water vapor and suffered considerable depletion of H_2O^{18}. It is therefore understandable why Greenland's snow contains less H_2O^{18} than precipitation in more southerly areas.

This simplified picture also explains the seasonal variation observed in precipitation in a single area (below). It can be expected that an air mass arriving in Greenland will have been cooled to a lesser degree in summer than in winter, and thus will have suffered a lower loss in H_2O^{18} during the summer. The differences in the H_2O^{18} in summer and winter snow in Greenland are, in some cases, 150 times as great as the experimental precision.

These seasonal variations in the isotopic compositions of snows in Greenland and in the Antarctic have interesting implications in the studies of glaciology. Natural labels depicting summer and winter layers permit correlation of stratigraphic layers extending over many kilometers. The isotopic layering persists in Greenland to depths of at least 400 meters. The ability to identify layers in snow and ice assists glaciologists in studies of rates of snow accumulation, flow patterns, and the general



Seasonal effect observed in the O^{18}/O^{16} ratios in Greenland snow. The less negative values of δ are for summer precipitation, and the most negative values are for the midwinter precipitation. The numbers on the abscissa represent the depth at which the samples are taken.



The variations with depth of the O^{18}/O^{16} ratios of Greenland ice taken from a depth ranging from 409.07 to 411.21 meters.

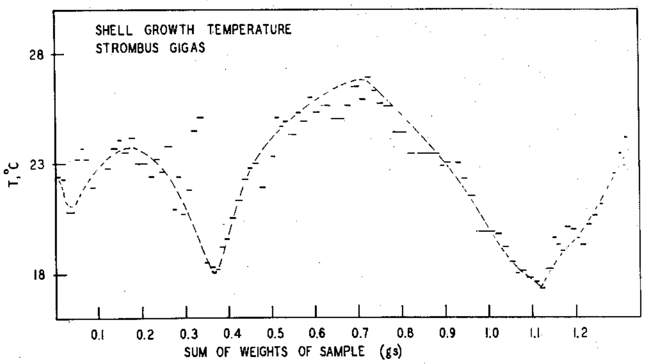
history of an ice cap.

Thus, a single difference in isotopic properties of water—the difference in vapor pressure of H_2O^{18} and H_2O^{16}—contributes to at least three different scientific fields, and more applications are possible.

TEMPERATURE STUDIES USING O^{18}/O^{16} VARIATION

When two or more oxygen compounds are formed in isotopic equilibrium with one another, the O^{18}/O^{16} ratios of the oxygen in the compounds are usually different. The partition of the isotopes of oxygen is temperature-dependent. It is therefore possible to use the partition coefficient or the isotopic fractionation factor between two oxygen compounds as temperature indicators. Because it is difficult to change the oxygen isotopic composition in crystalline minerals, silicate minerals of common rocks and fossil carbonate skeletons are capable of preserving their isotopic composition of oxygen over millions of years. Thus, in many of these rocks and shells there are very old isotopic records of the temperatures of formation of the rocks and minerals or of the temperature of the ocean in which the animals laid their carbonate skeletons.

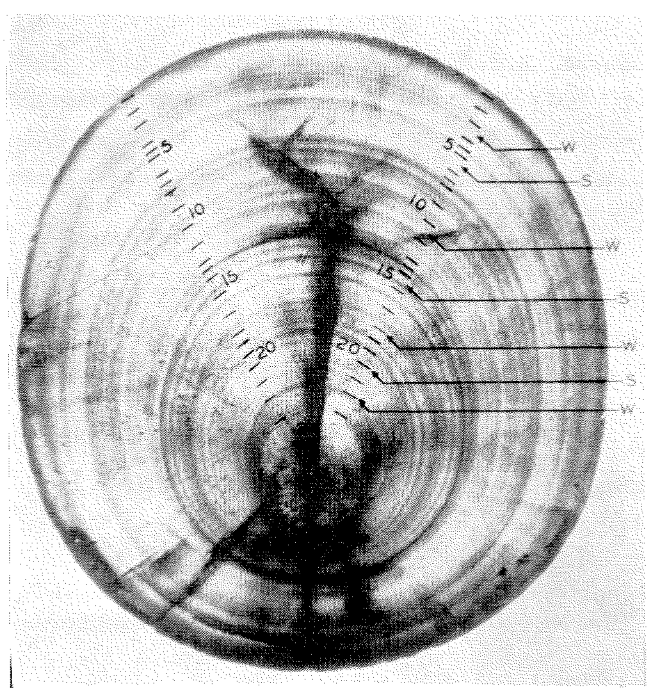
For example, the carbonate shell of a marine mussel, snail, or brachiopod has an O^{18}/O^{16} ratio 3 percent greater than does the water in which the animal grew. The O^{18} enrichment in the shell relative to that of the water decreases as the temperature increases. The precision of the mass spectrometer is such that we can measure a change in the O^{18}/O^{16} ratio equivalent to 0.5°C in growth temperature of a shell. By carefully grinding off the growth increments of a shell perpendicular to the growth lines,



The oxygen isotopic temperature record of increments of carbonate shell as sampled perpendicular to the growth lines. The length of each bar represents the weight of a sample ground off for several duplicate analyses. The average time interval represented by each bar could be a little over a week. (In collaboration with H. A. Lowenstam.)

we can get a series of samples representing growth periods of a few weeks.

Oxygen isotopic analysis of this series of increments provides a relatively detailed temperature record of the marine environment in which the shell grew. Such an isotopic temperature record can be observed in a recent snail, *Strombus gigas,* which grew off Bermuda in waters varying in temperature from a winter low of 18°C to a summer high of about 28°C. (Note above that the temperatures calculated from O^{18}/O^{16} ratio of the carbonate samples from the snail give a nice seasonal fluctuation.)



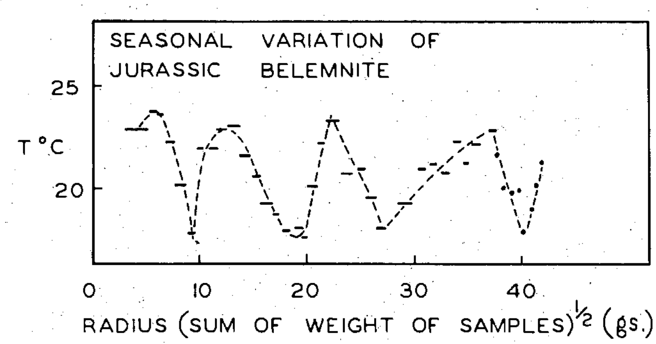
A cross section of a Jurrasic Belemnite showing the growth rings and the sequence of cutting. The w's and s's designate the positions of the winter and summer calcium carbonate growth increments.

While there are many complications associated with shell growth, the isotopic data can be used to determine what time of the year animals lay down their shells, whether their growth habits change with age, and other factors.

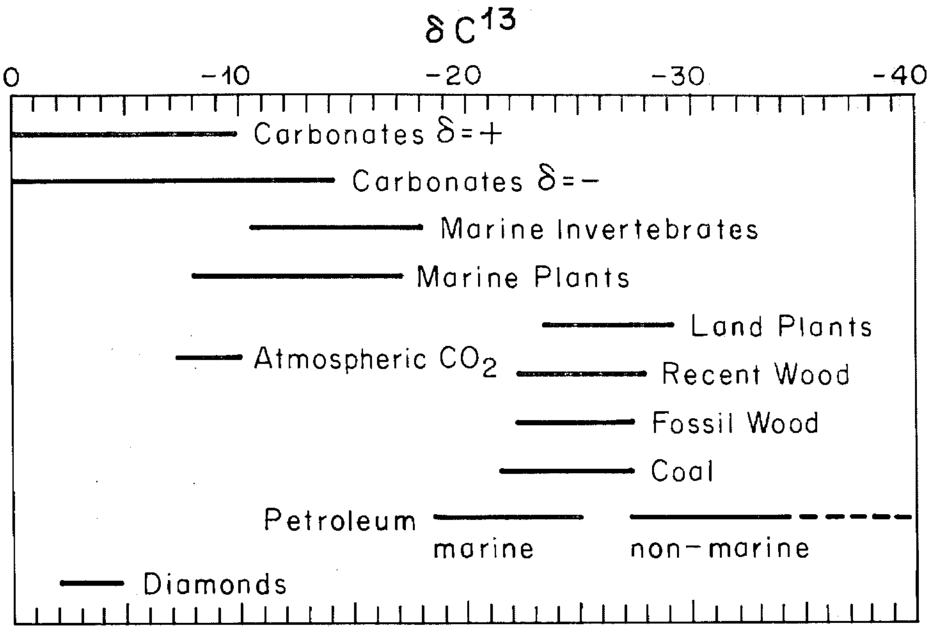
If we go back in time about 120 million years and repeat the sampling procedure in a Jurassic Belemnite fossil (below), we can also observe a seasonal variation. The oxygen isotopic composition of this very old fossil tells us that the animal grew a shell over a four-year period. Incidentally, the presence of such a seasonal variation represents good evidence that the fossil carbonate that we analyzed is the original carbonate laid down by the animal, since it is not probable that the carbonate of a recrystallized shell would have such systematic variations. This method of measuring paleotemperatures was first developed by Harold Urey and his co-workers at the University of Chicago some 15 years ago and has been used for measuring Upper Cretaceous (60-90 million years ago) temperatures as well as temperatures of the oceans during the glacial periods in the Pleistocene.

Since, in principle, any fractionation factor representing the partition of the O^{18}/O^{16} ratio between two oxygen compounds can give us a temperature, then the O^{18}/O^{16} ratio of coexisting silicates, oxides, and carbonates in rock samples can also serve this purpose. Indeed, the isotopic composition of coexisting minerals in common rocks has been used to determine a temperature of crystallization or of metamorphism of various rock types. The relationship between the fractionation factor and temperature is usually determined in the laboratory by equilibrating various minerals with water at different temperatures.

These simple examples illustrate our ability to use natural abundances of the isotopes of oxygen for labeling waters and measuring temperatures; however, we can safely state that the O^{18}/O^{16} ratio



The variations of the oxygen isotope temperature given by calcium carbonate increments with distance from the core of the Jurrasic Belemnite. (In collaboration with H. C. Urey, H. A. Lowenstam, and C. R. McKinney.)



δC^{13} values or C^{13}/C^{12} variations of carbon from various natural sources. (From Harmon Craig, UCSD.)

of *any* oxygen found in its natural habitat will give us some information about its origin and history. Atmospheric oxygen, for instance, has an O^{18}/O^{16} ratio unlike natural waters and unlike the oxygen given off by photosynthesizing plants. It is clear that the amount and isotopic composition of atmospheric oxygen depends on the amount of photosynthesis, respiration, oxidation of fuels, reaction with rocks, photochemical reactions, and volcanic emanation.

Associated with all these processes are accompanying isotopic fractionations, the studies of which will help us more fully understand the processes responsible for our atmospheric oxygen. Some work on this problem has already been done by Malcolm Dole of Northwestern University, but there is much promise of significant results in the continuation of this isotopic research.

Other common light elements, like hydrogen, carbon, and sulphur, have been studied isotopically, although less extensively than oxygen. Isotopic analysis of the C^{13}/C^{12} ratio in natural materials, as done by H. Craig of the University of California at San Diego (shown above), summarizes some of the isotopic geochemical studies. For example, the C^{13}/C^{12} ratio in terrestrial plants is low in relation to that of atmospheric CO_2 because the photosynthetic process prefers to fix $C^{12}O_2$ relative to $C^{13}O_2$. The C^{13}/C^{12} of the atmospheric CO_2 is mainly determined by its equilibrium with the large amount of bicarbonate dissolved in the ocean.

The reason for the low C^{13}/C^{12} ratio for petroleum is not quite clear, but some speculations have been put forth. One is that petroleum originates from lipids, which are found in most marine and non-marine plants. Lipids have a low C^{13}/C^{12} ratio relative to that of the rest of the plant, and are thus isotopically most similar to petroleum. If one is interested in processes involving carbon, there is a good likelihood that the understanding of the process can be enhanced by studying the isotopic fractionations associated with this process.

The isotopic variations in the S^{34}/S^{32} ratios in naturally occurring sulphides, sulphates, and sulphur have been measured in several laboratories, and this work has contributed significantly to the understanding of the origin of sulphur and sulphide ore deposits.

The H^2/H^1 ratios in waters and minerals have also been studied, and the research should contribute significantly to studies of geochemical processes involoving water and organic matter. The H^2/H^1 and O^{18}/O^{16} ratios in waters usually vary in a parallel manner. When the isotopic variations deviate from this parallel behavior we obtain information about non-equilibrium evaporation and condensation and about the nature of waters that have interacted with rocks and minerals at depth and elevated temperatures.

There are many potential uses for earth scientists in measurements of isotopic abundance variations in the light elements. That such measurements have been useful in many other branches of science becomes obvious if we consider that many chemical and physical processes may have an associated isotopic fractionation and that the study of this isotopic fractionation can enhance the understanding of these processes. The little that has been done in the stable isotope field shows a promise for an expanded effort in the future.

FOSSIL SENSORS

by Heinz A. Lowenstam

The history of life in the oceans during the last 600 million years is recorded by fossils in the sedimentary rocks of the earth's crust. Mineralized tissues in the form of skeletons are more commonly preserved as fossils than the soft parts of organisms, which are found occasionally as impressions or as degraded organic compounds. Hence, fossil skeletons have been the primary objects of paleontologic studies, and they have provided a wealth of information on the kinds of organisms that populated the paleo-oceans. By tracing changes in skeletal designs through geologic time, we have uncovered a rich new source of information on the evolution of marine life.

Questions arose early about the nature of the environmental conditions under which life evolved in the oceans in the last 600 million years and about the possibility that the environmental framework may have undergone evolutionary changes of its own. Two methods employed by students of ecology were found to be applicable in investigating these questions in fossils—adaptive morphologic traits and biogeography. These studies have provided a great deal of information on environmental conditions, such as relative degrees of water turbulence, the physical nature of the sea floor, current directions, and paleotemperature.

The relationships derived from these studies are still largely of a qualitative nature. John Wells has recently noted that the surface markings of coral skeletons show daily increments which are grouped in annual cycles. Extending the investigation to fossil corals, he found that the number of daily increments in an annual group has decreased in the last 600 million years from 424 to 365. These data are in agreement with the rate of deceleration of the rotation of the earth around its axis, calculated earlier by Walter Munk and Gordon McDonald.

Though much remains to be learned about the meaning and precision of biologically recorded geochronometry, the significance of this discovery is obvious, for it uniquely documents and quantitatively defines a significant change of the major variable in the environmental setting of life in the oceans during the course of its evolution.

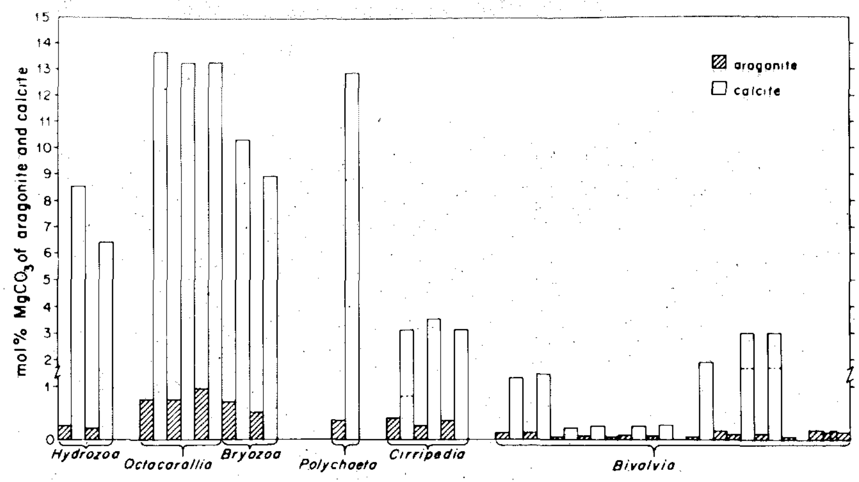
Skeletons are composed of mineral aggregates set in an organic matrix. The minerals, their chemistry, and the chemistry of the organic matrices are the products of biosynthesis by the organisms which elaborate them; hence they should embody basic information on the biochemistry and the environmental factors which affect them. This kind of information should be complementary to that which one derives from the skeletal morphology. These different source areas of information on biology, evolution, and paleoecology have been the subject of our studies.

Carbonate minerals are the most common biochemical precipitates in invertebrate skeletons of the recent marine biomass and of marine fossils. For this reason, carbonate skeletons have been more thoroughly explored than skeletons composed of other minerals. Studies to date indicate that skeletal carbonate minerals and their chemistry embody a wealth of biochemical and ecologic information. In most cases, several factors, through interaction, affect the biogeochemical properties of the carbonate minerals.

Biologic systems precipitate crystalline compounds of carbonate in the form of calcite and aragonite. Most species deposit only one of the two minerals. However, species in six classes of the animal kingdom precipitate both minerals in their skeletons. Elevation in environmental temperatures generally results in preferential increase in aragonite deposition, so that the aragonite-calcite ratio of the skeletal precipitates becomes higher.

This effect is best demonstrated by the mineralogy of the protective tubes of certain annelids (worms), which add carbonate only to lengthen the tube at the opening as the animal grows (right). Determinations of the aragonite-calcite ratios of consecutive growth increments of a species living at Bermuda, where the water temperatures fluctuate widely between winter and summer (from 16°C to 29°C), show cyclic changes of increasing and decreasing aragonite-calcite ratios over a range of 30 percent.

At the outer barrier reef of Palau in the Caroline Islands, the water temperatures are 28°C ± 1°C throughout the year. All other environmental factors remain similarly constant. If temperature were

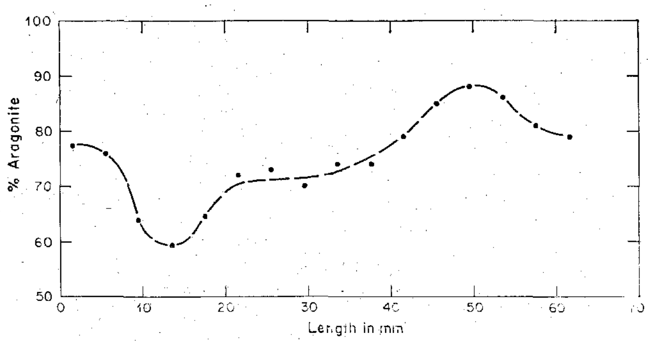


Histograms showing that the mol% of magnesium is always lower in aragonitic than in calcitic parts of the shells of organisms that lived in a nearly constant water temperature.

the only factor to control the aragonite-calcite ratio of skeletal carbonate precipitates, one would expect to find the same ratios in all temperature-sensitive species. Instead, we find widely differing ratios in the skeletal carbonates that occupy the same microenvironment at Palau. These data indicate that the biochemistry of the species acts as a filter for modifying the effect of temperature on the aragonite-calcite ratios of their carbonate precipitates.

A temperature effect on the magnesium contents of skeletal carbonates is always shown by an increase of the concentration of this element with elevation in environmental temperatures. This relationship has been found in calcitic and aragonitic precipitates of skeletal carbonates from all species of carbonate-secreting metazoa investigated to date. This contrasts sharply with the species-defined selectivity in temperature effect on the carbonate mineralogy. Where temperature is the only ecologic variable, and where the water temperatures are the same throughout the year, as at Palau, the organic calcitic precipitates are always higher in magnesium than aragonitic precipitates (above).

Strontium uptake by skeletal carbonates in response to temperature is like that of magnesium



Aragonite-calcite ratios in consecutive growth increments of annelid worms, showing cyclic changes in the ratios over a range of 30 percent owing to temperature fluctuations.

in reflecting the modifying effects of the crystal chemistry of the mineral phase and of the biochemistry of the species. There are, however, some basic differences when compared to the uptake of magnesium. Strontium is preferentially accommodated in the crystal structure of aragonite as compared to calcite. Consequently, we find that the aragonites precipitated by species of all phyla, with the exception of three classes of mollusca, have noticeably higher Sr contents than the calcitic precipitates. Temperature tends to have an inverse effect on the Sr uptake of all species examined so far; the Sr concentrates decrease with elevation in environmental temperatures.

Another property known to be affected by environmental temperatures is the O^{18} content of the skeletal carbonates. The O^{18} content of carbonates laid down in isotopic equilibrium with the surrounding waters is dependent on the O^{18} content of the water, and on temperature. Since the isotopic composition of mean ocean water is by definition 0, temperatures can be calculated from the O^{18} content of samples derived from the well-mixed oceanic reservoir without requiring a water correction. The O^{18} content of isotopic-equilibrium precipitates decreases with elevation of temperature by about 0.2 percent per degree Centigrade. Only two biologic systems—Coelenterata (which includes corals) and Echinodermata (including sea urchins and starfish)—are known to precipitate skeletal carbonates out of isotopic equilibrium with their surrounding waters.

Another variable of the external environment that determines the isotopic composition of the skeletal carbonates is the chemical composition of the sea water. It has been known for some time that the shells of some molluscan species decrease in size and degree of calcification with decrease or increase in salinity as compared to mean ocean water. It has also been shown that the dwarfing caused by decrease in salinity in some species is accompanied by an increase in the aragonite-calcite ratios, with values in excess of those found in shells grown at the same temperatures in habitats with water of mean ocean salinity. Similarly, there are data—for brachiopods, among others—which show that shells from highly saline and fresh-water-diluted sea waters have Mg and Sr contents which differ—in some cases radically—from those grown at the same temperature in habitats of mean ocean salinity. We are currently growing a variety of marine species under controlled conditions in our laboratory at Caltech to determine the effects of changes in salinity over the range found in the oceans, and to test the influence of Mg/Ca and Sr/Ca ratios in sea water on the ratios of these ions in skeletal carbonates.

Most investigators of deep sea organisms are inclined at present to attribute the depth zonation of marine biota in the intermediate and low latitudes to a decrease in water temperatures with an increase in depth, and to assign to increases in hydrostatic pressure a minor, ill-defined role. This seems justified in the case of species which range from shallow water at high latitudes to increasingly greater depths in low latitudes, for some species are known to occupy a depth range of 9000 meters—which corresponds to a range of change in ambient pressures equivalent to 900 atmospheres. Environmental temperatures over the entire range differ at most by 3° to 4°C.

It seems clear that, in these particular cases, the limiting factor of their depth distribution is temperature rather than differences in ambient pressures. It has been pointed out also that the upper limit of the deep sea biota in general coincides more closely with the 4°C isotherm than with any particular depth. Yet only a few of these deep sea species range into the shallow waters at high latitudes where the temperature regime is similar to that of their habitat range. Hence, there is the possibility that hydrostatic pressure may be the limiting factor in the depth distribution of many species. An independent measure of depth would be most desirable in the study of fossils, and hence the question of a possible pressure effect on one or several of the skeletal properties is of major significance for paleo-depth determinations.

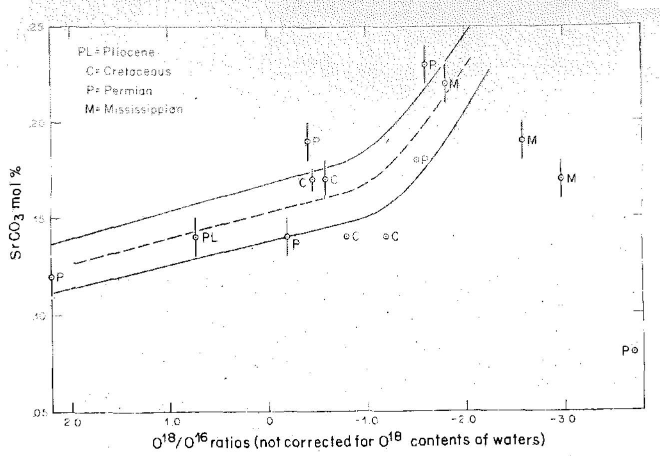
For this purpose we have initiated laboratory studies of the biogeochemistry of skeletal carbonates from multicellular organisms which have a wide depth distribution, in order to determine tolerance ranges in hydrostatic pressure of species from moderate depth. Considering samples from nature with a wide depth distribution, we selected bottom-dwelling organisms which have either calcitic or aragonitic skeletons in all species of the same class under all known environmental conditions. Their Mg and Sr contents show either poor or no correlation with environmental temperatures, whereas there are systematic changes in concentrations when these data are related to the depths from which samples were taken.

Our pressure experiments have been conducted in an open, high-pressure apparatus that permits injection of food, and the pressure chamber has a plastic window for observing the animals. The system was designed by James Westphal, senior research fellow. Individual gastropods, recovered by dredging from a depth of 800 meters, were found to tolerate gradual increase in pressurization from atmospheric conditions to pressures equivalent to 80 atmospheres, as well as instantaneous depressurization back to 1 atmosphere—as we discovered when the pressure system accidentally failed. The maximum pressures tolerated by the individuals are near the maximum depths from which the samples were taken. Lack of records of this gastropod in the surface waters of the area where these individuals lived indicates that factors other than hydrostatic pressure prevent the species from occupying shallower depth habitats.

Thus, while we still know very little about the subject, it seems that hydrostatic pressure is an important environmental control. It may limit the distribution of species, and, within the range that they occupy, it may affect their biochemistry, which in turn finds an expression in the uptake of the major trace element of skeletal carbonates.

It is becoming clear that the minerals and their chemistry from skeletal carbonates monitor a wealth of information, ranging over the characterization of certain biochemical responses of the organisms to the temperature, the salinity, the sea water chemistry, and the hydrostatic pressure conditions of their environment. The biochemistry of the species basically determines the kinds of minerals precipitated by an organism. It regulates the levels of the trace-element concentrations at different body sites and, in particular, in the tissues which are involved in mineral precipitation. The ability of some biochemical systems to discriminate strongly against certain cations from the external medium explains why there is no apparent crystal chemical partitioning shown by them between the calcite and aragonite phase in the mineral precipitates.

The effects of environmental factors on the biochemistry of the organisms are transmitted invari-



The relationship between O^{18}/O^{16} *ratios and* $SrCO_3$ *is depicted here in modern shells (lines) and in fossil forms (letters) as old as 250 million years. Conformity of the relationships shows that no marked change has occurred in the biochemistry of the organism or in the environment. The two M points to the right indicate post-depositioned alteration of these two samples.*

ably to the trace-element concentrates of the mineral precipitates, and less frequently to the kinds of mineral phases which are precipitated by certain tissues. There are noticeable differences in the responses by different biochemical systems to environmental controls. These differences are reflected by differences in concentration levels and by the magnitude and direction of deviation on these levels of the trace-element contents and the aragonite-calcite ratios in the different systems.

Methods for applying all this information to the study of the environmental conditions of marine life in the geologic past by means of fossils require proof that we are dealing with the original mineralogy and its chemical properties. In the case of the mineral phases and their trace-element contents, one may ask whether these have undergone changes strictly in response to biochemical evolution, and, in turn, to ecologic variables. There is also the distinct possibility of changes in time in the chemistry of the oceans.

In the face of the large number of unknowns, the only recourse available at present is to compare the relationships of at least two geochemical properties in fossils which show no physical evidence of mineralogic change, with those of related living forms where these relationships have been defined. If relationships in fossils are the same as in recent species, their biogeochemistry is considered the original one, and the factors affecting the particular properties have remained the same. If the original composition is preserved, and one or several of the ecologic variables which affected them underwent evolutionary changes, one would expect systematic changes in their relationships with increase in geologic age. This method of multiple approaches has been applied by us to articulate brachiopods, because fossils of this class are amply represented in the sedimentary rocks of the last 600 million years.

The relationships of the oxygen isotopes to the strontium contents for samples ranging back from the present to 250 million years ago are illustrated at left. The samples numbered by the letter M indicate that one can detect by this method even small diagenetic changes in the isotopic composition and in the strontium contents of the shells. All three samples are shells of the same species from the same deposit at the same locality. The samples showing the greatest divergence from the relations shown by the living forms were found loose on the weathered surface of the deposit; the one of lesser deviation from the weathered zone of the deposit, and the one showing agreement with the relations for living forms was derived from depths in the fresh shale of the deposit. We can also show that the changes in relationships among the samples are precisely what one would expect on grounds of theoretical considerations when shell carbonate becomes altered under the influence of fresh water.

The fact that some of the samples ranging back 250 million years in geologic age show similar relationships in their O^{18} and Sr concentrations indicates that the biochemistry of these brachiopods has not changed and that the isotopic and strontium contents of the ocean were similar to those of the present. Comparison of their Mg content with the O^{18} content indicates that only two low-magnesium samples show agreement in their relation to the O^{18} and Sr content with those in living species. In other samples the Mg content is lower than in living species. This is in agreement with observations on other fossil samples—that the Mg contents in high magnesium calcites in fossil skeletons are more susceptible to alterations in the rocks than are the O^{18} and Sr contents. Because it is highly improbable that three biogeochemical properties with different behavior should agree in their relationships with living forms, the Mg contents of the two samples with low concentrations are considered unaltered. This would indicate that the Mg contents of the oceans have not changed in the last 200 million years.

These examples indicate that it is possible to get a variety of biologic and environmental information about the chemistry of skeletons. There are numerous examples to show that this can be applied to fossils, and, with the aid of such information, we expect with more data to get a better picture of the evolutionary history of life in the ocean and of the changes in the oceanic environment.

San Francisco—April 1906

California Earthquakes

by Charles F. Richter

The known history of California earthquakes begins with Spanish exploration and settlement. On July 28, 1769, the expedition of Gaspar de Portolá, which had set out from San Diego to investigate the reported fine harbor of Monterey, was in camp on the Santa Ana River near the present site of Olive in Orange County. They were alarmed by a locally strong earthquake. It is noteworthy that they continued to feel aftershocks for several days, until they were well up the coast in what is now Ventura County. This suggests that the first known earthquake was not a local affair but possibly a major earthquake on one of the principal faults.

San Gabriel Mission was founded in 1776. Earthquakes there were then so frequent that Father Serra referred to the San Gabriel Valley as El Valle de los Temblores, or Earthquake Valley.

In December 1812 there were two important earthquakes; accounts at first became confused together but have now been disentangled. The one on December 8 occasioned the first loss of life due to earthquakes in California; a tower at San Juan Capistrano Mission collapsed, and 40 of the congregation were killed. There was also some damage at San Gabriel. On December 21 there was a much larger earthquake farther west which wrecked the westernmost mission, Purisima, and damaged others as far east as San Fernando. This major earthquake appears to have originated in or near Santa Barbara Channel. There are unsatisfactory reports of a sea wave caused by it. The late Professor G. D. Louderback, who investigated original documents of the period, was convinced of the reality of this wave. A ship then anchored off Gaviota reported that the water was seen splashing up in the canyons —from which Louderback inferred that it might have risen to 50 feet. This whole matter has lately assumed importance in estimating possible risks to installations on the coast, but opinions differ widely.

Small waves are known to have been caused by earthquakes on our coast, notably one in 1927 which rose to about eight feet along the west coast of Santa Barbara and San Luis Obispo counties. The only recorded disaster from such waves on our coast occurred at Crescent City in March 1964, when the waves caused by the great Alaskan earthquake piled up there and caused local flooding.

Louderback clarified the history of two important early earthquakes—one in 1836 on the east side of San Francisco Bay, probably associated with the Haywards fault, like that of 1868; and one in 1838, almost certainly on the San Andreas fault, like that of 1906, and probably also a major event.

Of much public importance is the historical record of a great earthquake on January 9, 1857, which originated on the San Andreas fault in southern California; faulting probably then extended from San Luis Obispo County to a point north of San Gorgonio Pass. Fort Tejon, then an army post, now a historical monument, was near the middle of the faulted extent, and the buildings were considerably damaged. There is much evidence that this earthquake was comparable in magnitude, extent of faulting, and local intensities with that of 1906. The 1857 earthquake is now the principal factor in considering earthquake risk to existing or projected construction and development in much of southern California, since at many sites a structure which would survive a repetition of the 1857 event probably would not be critically damaged by other earthquakes.

The Haywards earthquake of 1868 was associated with displacements on the Haywards fault, which runs through the heavily settled area on the east side of San Francisco Bay (and through the grounds of the university at Berkeley). The area of damage included part of San Francisco, where this was called "the great earthquake" until 1906.

In point of magnitude, the Owens Valley earthquake of 1872 may have been the largest in our area during the short historical period. Fault scarps and other effects were produced which can still be seen. Most of the town of Lone Pine was destroyed, with a loss of 27 lives.

A little-known but widely felt earthquake in 1885 originated in the mountainous area northwest of San Luis Obispo and may have been associated with the controversial Nacimiento fault.

In April 1892 two earthquakes seriously damaged many of the towns in the Sacramento Valley, notably Vacaville, Winters, and Dixon.

Two strong earthquakes occurred in 1899 in southern California: one in July, probably on the San Andreas fault, which caused many slides in Cajon Pass; and one on Christmas day, which heavily damaged the town of San Jacinto, though its center was on the San Jacinto fault in the mountains to the southeast.

Many books and papers have been written about the great earthquake of April 18, 1906. The disaster at San Francisco was of course of great human interest and drew attention to possible preventative measures. Seismologists and geologists were greatly concerned with the conspicuous lateral displacements along the San Andreas fault. Although the relation between earthquakes and faulting had been well formulated in Japan following an earthquake there in 1891, the new observations of 1906, substantiated as they were by exact observation of the displacements of survey monuments, led to the clear formulation by Harry F. Reid of the elastic rebound theory of earthquakes.

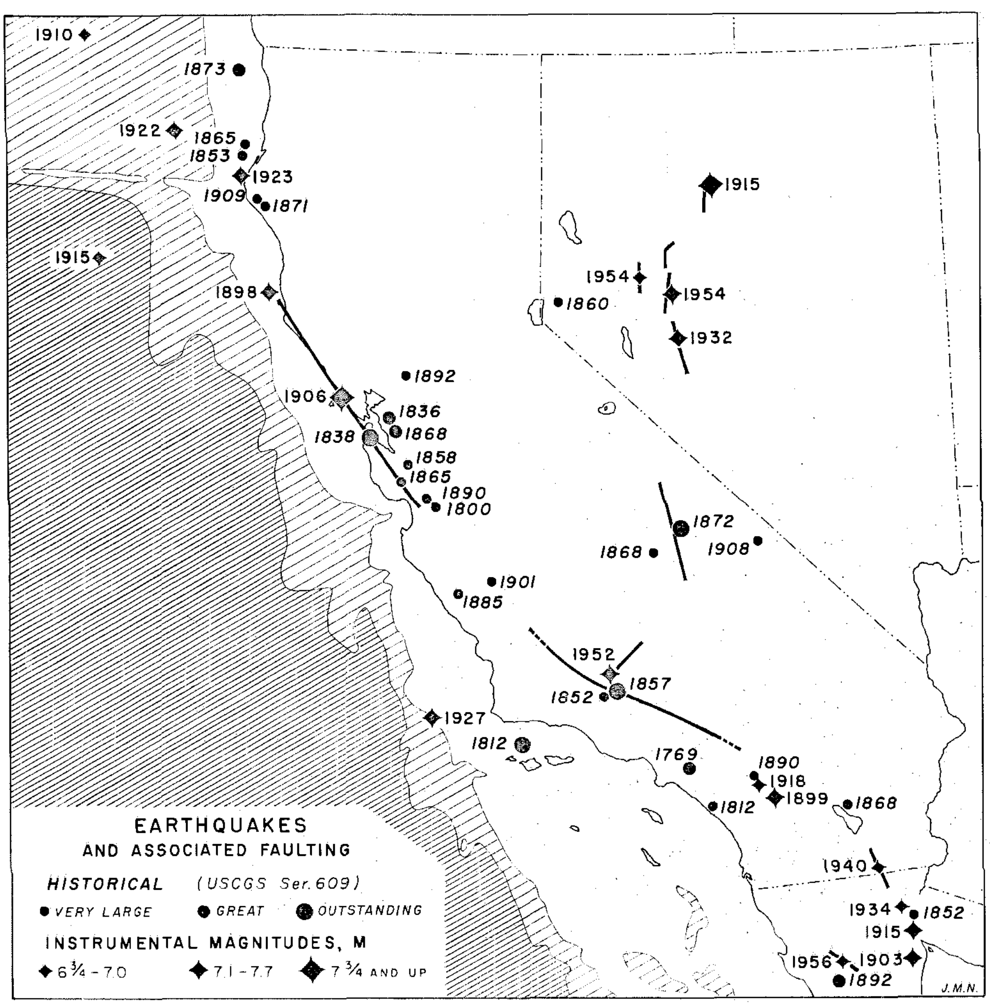
Misapprehensions and misstatements about the disaster of 1906 still persist. One of these consists in underplaying the losses in San Francisco due directly to earthquake damage; while much less than those due to fire, they were nevertheless large. Of course the fire losses were due in large part to failure of the water supply by disruption of the main supply lines from the reservoirs, which ran along the San Andreas fault line, and by breaking up of lines from local tanks and reservoirs due to shaking and sliding of the ground in the city.

Loss of life is sometimes estimated as low as 390, though 700 is probably a better guess. We shall never know how many perished in the fire-swept areas, from which bodies could not have been completely recovered. Outside San Francisco the loss of life is better documented; it amounts to over 200, including 61 at Santa Rosa, 19 in San Jose, and the shocking figure of at least 112 at Agnews State Hospital near San Jose.

In San Francisco the earthquake provided one of the best documented cases of relation of earthquake effects to ground condition. All the effects of heavier shaking, by which the ground was significantly deformed, were on the area of filled land surrounding the lower part of Market Street, or on small areas of fill in the hills, or on the sands toward the coast. The new post office on Market Street was just outside the area of made land; it was relatively undamaged. Much is sometimes made of the fact that the Ferry Building, with its conspicuous tower, survived; it is not generally known that the tower had to be torn down and rebuilt.

This was a truly great earthquake; it cut a broad swath of damage extending for over 200 miles along the San Andreas fault. It was felt by persons over most of California, and into Oregon and Nevada. It wrote spectacular seismograms at distant stations. One should bear these facts in mind when persons impressed by local earthquake disasters like our Long Beach earthquake of 1933, or like the one which cost 12,000 lives in Morocco in 1960, insist that these two must be listed as major earthquakes. When considered from the point of view of risk, safety, and disaster planning, such classifications are seriously misleading. Awareness of the inadequacies of the existing classification procedures led to setting up the magnitude scale. When we assign a magnitude 8.3 to the 1906 earthquake and 6.3 to the Long Beach event, this is not a vague or arbitrary estimate; it expresses the observed fact that the ground disturbance, as measured by seismograms at comparable distances from the two occurrences, was of the order of 100 times greater in 1906 than in 1933.

In many countries earthquake disasters have led to the setting up of scientific, government-sponsored agencies to work toward the prevention of future disasters. In California the events of 1906 led to the organization of the Seismological Society of America; but there was no further support either from governmental sources or from the general public. Instead, there was a public policy of hushing up discussion of earthquakes on the shortsighted excuse that it might be bad for business; and it was customary to refer to the disaster



Larger earthquakes of the California region. Extent of faulting is indicated by dark lines.

Santa Barbara Mission—after the Santa Barbara earthquake of 1925.

of 1906 as a fire only. This policy was successful in it main objectives: It remained possible to construct commercial and public buildings carelessly and cheaply, with no attention to the possibility of earthquake shaking. There was very little effective building regulation of any kind in California until the 1920's. At the same time, local insurance organizations and agents, themselves deceived and unaware of the true risk, were selling earthquake coverage without regard to actuarial soundness.

For some years following 1906 there were relatively few noteworthy earthquakes in California; the main centers of population were not affected. There was a definite increase in activity beginning about 1915. In June of that year a destructive earthquake affected most of the towns in Imperial Valley; in October there was a major earthquake with faulting in central Nevada, in a very thinly settled area. In 1918 there was a large earthquake on the San Jacinto fault, which again severely damaged the town of San Jacinto. A minor earthquake in June 1920 damaged the town of Inglewood and led to the identification and naming of the Inglewood fault, one of the principal sources of earthquake risk in the metropolitan Los Angeles area.

The Santa Barbara earthquake occurred in 1925. It had a magnitude of about 6.3, close to that of the later Long Beach earthquake. Although some millions of dollars in damage was caused, and at least 12 persons were killed, the disastrous effects were not extensive because there were few centers of population in the heavily shaken region. However, insurance organizations were disturbed by the amount of claims that had to be settled, and there was a sudden tightening with reference to earthquake insurance. Competent inspection of damaged buildings at Santa Barbara showed such serious deficiencies that considerable impetus was lent to efforts then being made by business, engineering, and scientific organizations to draft more appropriate building codes and bring about their enforcement.

The Long Beach earthquake of 1933, originating along the Inglewood fault, was a major disaster because of the relatively urbanized character of the most severely shaken area, and because of constructional deficiencies as bad or worse than those seen earlier. The conspicuous failures of school buildings at that time led to the first action by the state of California, in the form of what is usually termed the Field Act.

This legislation prescribes satisfactory standards for new construction of schools and other public buildings. It is not retroactive and does not directly lead to safety in buildings constructed prior to 1933. It does provide for proper inspection. If a school building is inspected and found unsafe, the school board members become personally responsible for any consequences. This rather rigorous provision was invalidated in practice for many years; it was held that if at an election the voters failed to authorize funds for replacement or reconstruction, responsibility was thereby removed from the school board. This way out was enthusiastically adopted, and in numerous California communities, after the failure of bond elections, unsafe buildings were returned to use. About two years ago the office of the State Attorney General issued a ruling invalidating this interpretation. The matter is not yet finally settled, since no test case has entered the courts, but the immediate effect has been an effort in many communities to bring school structures up to Field Act standards.

In 1940 the Imperial Valley earthquake provided a good objective test of the Field Act code; schools constructed before 1933 were more or less damaged, while those constructed under Field Act provisions were hardly affected. This earthquake was accompanied by faulting similar to that of 1906 in local horizontal displacement, but much less extensive—appearing for about 40 miles along the Imperial fault, which is a minor member of the general fault system related to the San Andreas fault. Of special interest were the peculiar deflection of the fault break in crossing the open excavation for the unfinished All-American Canal, and the displacement of bicycle tracks crossing the fault line after the main earthquake, while aftershocks were going on. Only a fraction of the economic loss was due to building damage; the fault breaks disorganized the entire canal system distributing water, particularly to the west side of Imperial Valley, and expensive and hurried reconstruction was necessary. At El Centro a set of strong-motion seismographs installed by the Coast and Geodetic Survey wrote the first good records obtained of an earthquake with locally damaging intensity; these records have become a sort of standard in engineering discussion and investigation with reference to earthquake-resistant construction. The results are of great value, but sometimes have been interpreted too positively without recognizing that this is only one earthquake, and in some ways a peculiar one.

A high point in the study of earthquakes in southern California was reached with the occurrence of the major earthquake in Kern County on July 21, 1952. Of magnitude 7.6, it was the largest earthquake originating within California since 1906. It is still often referred to as the "Tehachapi" earthquake, because the town of Tehachapi had much conspicuous damage (mostly to very weak structures) and the majority of casualties. The epicenter, on the White Wolf fault, was at the edge of Caltech's network of stations, which were soon supplemented, at first by portable instruments recording aftershocks at many locations, then by new permanently established stations. One of the latter, at the fire station near Woody, Kern County, in the foothills of the Sierra Nevada, proved to be a very favorable location for recording and is one of the most sensitive seismological stations now operating.

Although the White Wolf fault had been mapped and was suspected of being associated with small recorded earthquakes in its area, no one expected it to be the seat of a major earthquake with surface faulting. Actual fault displacement was responsible for the most costly damage—the ruining of railway tunnels on the Tehachapi route, which put that line out of service for weeks.

Epicenters of all the larger aftershocks were determined and mapped in detail, giving an unusually accurate picture of the seismic event as a whole, and affording much data for discussing the mechanism of earthquakes.

Since the epicenter of the main event was determined with exceptional precision, recordings at stations all over the world were available for a new revision of the time-distance tables for seismic waves.

An event with important bearing on earthquake risk was the occurrence of a moderate aftershock (magnitude 5.8) on August 22, with the epicenter much closer to Bakersfield than the main earthquake, so that this aftershock was actually more damaging in that city. Study of the damage in both earthquakes was of much engineering value.

We set our teeth and bear with our feelings when the popular press reports that we are "overdue" for a great earthquake in southern California. If this means anything, it means that from various lines of evidence we guess the interval between such earthquakes to be, on the average, about 100 years. The last such really great earthquake was in 1857—so take it from there. Similarly, we are long "overdue" for one of the smaller but potentially damaging earthquakes, comparable to the 1933 Long Beach shock, which typically have occurred on the average of once every two to three years. The last such earthquake in southern California was in March 1954, centering in the Santa Rosa Mountains, so that it attracted relatively little public attention.

Very exciting to seismologists have been the well-observed phenomena of the earthquake in the Parkfield-Cholame area on May 28, 1966. Pre-seismic cracking; fault displacements of a few inches, continuing in aftershocks; acceleration up to one-half of the gravitational acceleration, registered by a strong-motion instrument a few hundred yards from the fault—these are reported on in publications from our own staff and from those of four or five other organizations. There has never been such a concentration of talent and equipment for the investigation of a small earthquake in this country, though such things have been done in Japan and in the Soviet Union on many occasions.

Whatever the California citizen may feel in looking forward, the seismologist is filled with hopeful anticipation as our earthquake history continues to unroll.

Looking down to the floor of Meteor Crater, Arizona—a depression 3,168 feet in diameter and 500-600 feet deep, formed by the impact of an iron meteorite perhaps not much more than 100 feet in diameter. Blocks in foreground are rock fragments thrown out of the crater to form a low detrital rim-ridge. Most craters on Mars and Moon are thought to be of similar origin.

Geomorphology In The Space Age

by Robert P. Sharp

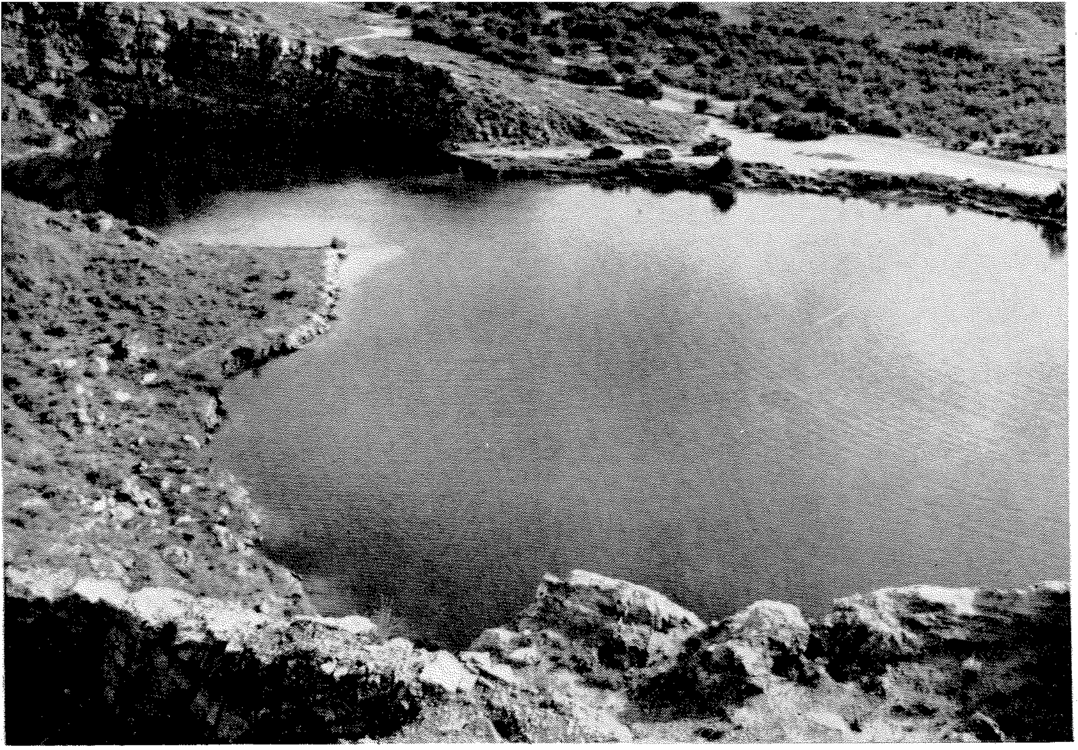
Geomorphology, the science of land forms, is one of the older classical subdisciplines of the earth sciences. Nonetheless, it maintains an encouraging viability within the framework of modern scientific endeavors. It was no accident that some of the major geological explorers of the Far West—Powell, Dutton, Russell, and Gilbert, to name a few—were accomplished geomorphologists. Geomorphology involves techniques which an experienced observer can apply to an unknown terrain with minimal equipment and maximum product. Observations of surface forms and features during their wilderness travels enabled these men to draw meaningful conclusions concerning the geological makeup and evolution of the regions traversed.

One of the great delights of science is the continual development of new fields to conquer. Currently, the geomorphologist has two enticing *terra incognita* to consider: the floor of the ocean and the surfaces of the moon and other planets. Both are well worth attention, but currently at Caltech our efforts focus more on the moon and planets.

For good reason, the early space probes launched toward Moon and Mars had as a principal mission the photographing of the surfaces of those bodies. Photographs provide the greatest amount of information, at the lowest cost, about lunar and planetary surface conditions. The interpretation of such photographs is largely, but not exclusively, a geomorphological procedure. The best analog from which to work is the earth, which geomorphologists know well.

Even the earliest telescopic observations of Moon showed its surface to be pocked with craters. What makes natural craters on Earth? Meteorite impacts, volcanic explosions, and subsurface collapses of a variety of origins are common causes. Painstaking study of earthly craters has led most investigators to conclude that lunar craters are largely the product of meteoroidal impact. Still there are those who stoutly support a volcanic explosive origin for some, if not a majority, of the lunar craters; and most serious students of the moon are far from ready to assert that there are no volcanic features such as craters, cones, lava domes, lava flows, and sheets of volcanic cinder and ash on its surface.

Furthermore, Ranger and Orbiter photos reveal small craters and linear features on the lunar surface not unlike forms created on Earth by collapse into subsurface openings. These features have caused some observers to speculate on the possible existence of an ice layer beneath the lunar surface that locally melts or evaporates, leading to the for-



So-called Bottomless Lake, New Mexico, affords a good example of a crater-like feature formed by collapse owing—in this instance—to removal of underlying limestone beds by ground-water solution. Many of the smaller craters on the moon look like collapse features, but the possible causes of lunar collapse remain a subject of speculation.

mation of collapse features on the surface. Whatever their cause, collapse features do seem to exist on the moon's surface.

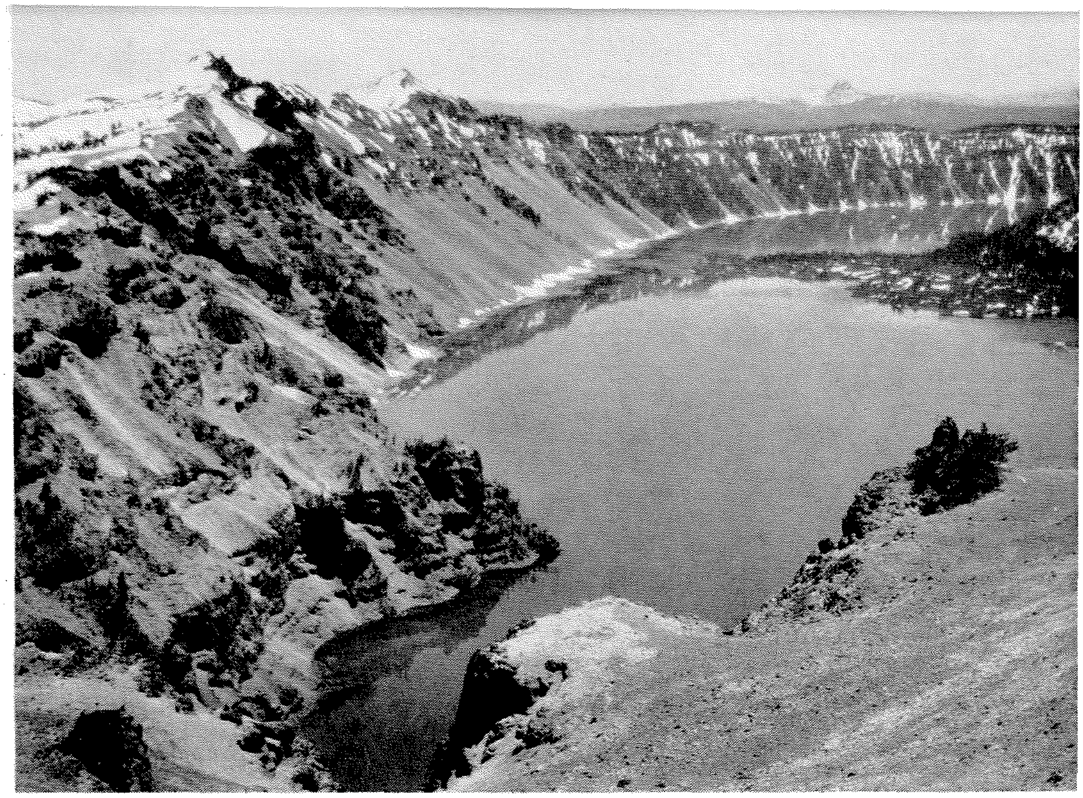
One thing made clear by Ranger and Orbiter photos is the considerable modification undergone by many lunar craters. Great slump blocks are seen on the inner walls of large craters, and loose rubble has clearly flowed, crept, or slid down the crater walls. These sorts of transport are old friends to the geomorphologist, and he quickly appreciates their role in altering craters and other topographic forms. However, the principal process modifying lunar landscapes is something he is less familiar with in terms of earthly analogs.

Each time a new crater is formed on the moon, whether by meteorite impact or volcanic explosion, a curtain of ejected material is sprayed at high velocity and for great distance over the surrounding terrain. These flying fragments, unimpeded by any atmospheric envelope, impact and abrade everything in their path. As they hit the surface, a whole spectrum of secondary fragments can be launched which do likewise. Not only does the ejected material erode, but it blankets the terrain where it comes to rest. This combination of transport, erosion, and blanketing has been endlessly repeated through long eons of time and has greatly modified topographic features on the lunar surface.

Man has been excited by the surface appearance of Mars ever since he trained his first primitive telescope on the red planet. The dark areas (called *maria*), the light areas (called deserts), dark streaks (canals), polar caps, clouds, and the red color have intrigued him and have provided a fertile basis for much debate and speculation. The exciting thought that Mars, possessing an atmosphere, might provide an environment favorable to highly developed forms of life has slowly been dispelled by spectroscopic, polarimetric, infrared, and other indirect observations. Present-day information suggests that the martian environment could at best probably support only the simplest forms of life, perhaps unlike anything found on Earth. Mars is very dry—so dry that liquid water may never exist on its surface. And it is cold—the mean temperature for the whole planet probably being between -80° and -90°C (-112° to -130°F). Its atmosphere is very thin (0.5 to 1.0 percent of that of Earth) and composed predominantly of CO_2. The martian surface is also subject to a high flux of ultraviolet radiation.

Man's first close look at the martian surface provided by the spectacular Mariner IV photos brought the planet for the first time within the grasp of geomorphologists. Mars has craters—lots of them, of all sizes, characteristics, and degrees of preservation. Like lunar craters, they are probably of impact origin, but there is as yet no absolute proof of this. Martian craters, however, are less numerous than lunar craters, generally shallower, and with gentler slopes. Clearly they have been modified and even destroyed to a greater extent than lunar craters by some processes of erosion or deposition more effective on Mars than any combination of processes active on the moon. Even a greater facility for isostatic (plastic) readjustment in the martian crust than in the lunar crust would not compromise these

Crater Lake, Oregon, is a splendid example of a caldera —of which there are a number on the earth's surface. These huge craters, miles in diameter and thousands of feet deep, are formed by collapse following volcanic eruptions. If volcanism occurs on Mars or Moon, some of the lunar or martian craters could be calderas.



conclusions about such processes.

On Earth, liquid water is an essential element in chemical weathering, in the breakup and transport of rock debris by freeze and thaw, and in other processes producing and transporting rock detritus on slopes. Without liquid water, processes that might modify topographic forms on the martian surface are not easily deduced. Consideration of all possibilities, particularly in comparison with the moon, leads to the conclusion that wind and thermal creep are particularly worthy of consideration.

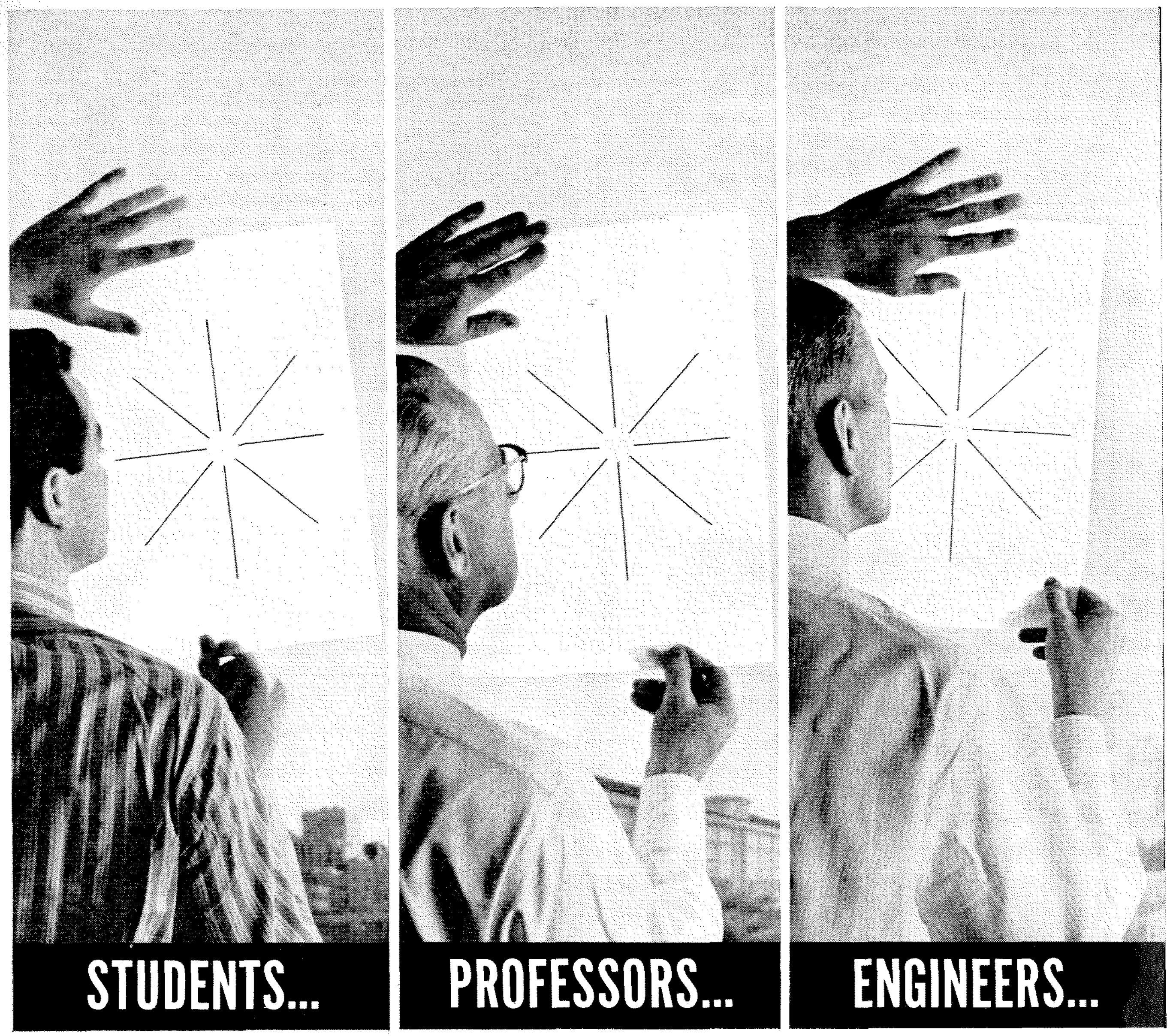
Wind has long been favored as an agent of transport, erosion, and deposition on Mars because the great yellow clouds episodically obscuring parts of its face are thought to be dust. This is a reasonable hypothesis, but there are some problems. Wind does not pick up fine dust easily, and the wind velocities required for effective eolian activity on Mars are impressively large, possibly in the neighborhood of 100-200 miles per hour. This is well in excess of the observed velocity of cloud movements across the face or along the limb of Mars. Still, the rigorous thermal regime of that planet gives some theoretical basis for postulating high wind velocities, so the possibility of effective eolian action on Mars must not be too greatly discounted. However, if wind is an effective agent on Mars, it probably modifies landscape features more by burying them with wind-blown sand and dust than by erosion.

Since the surface of Mars is heavily scarred by craters, it is a reasonable inference that its surface is mantled by a relatively fine rubble not unlike that revealed on the moon by Surveyor photos and experiments. If this be so, then another process of crater modification merits attention, namely thermal creep. The temperature regime of Mars is harsh, and daily extremes range over a span as great as 132°C (238°F), far surpassing anything known on Earth. Loose rocky debris creeps slowly downslope under repeated expansion and contraction caused by temperature changes. This could be an extremely important process on Mars, and much more effective there than on the moon because of the greater frequency (daily compared to monthly) of temperature change.

The rubble mantling slopes on both Moon and Mars will also creep downslope because of vibrations set up by meteoroidal impacts or seismic events. Vibrations of both origins may be more abundant on Mars than on Moon, and this could be a third but possibly less important influence contributing to the greater relative deterioration of martian topographic forms.

Time will tell how near to the fact are these speculations about geomorphological processes on Mars. However, this now becomes an exciting game because we are going to get more and more facts with which to test these speculations.

Some observers of the scene have suggested that, ideally, the first man to land on the moon should be a geologist. Some of us would go so far to say he should not only be of the genus *Geologist* but of the species *geomorphologist*—one who understands the meaning of topographic forms—because that is certainly what he is going to see the most of during the first short visit.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