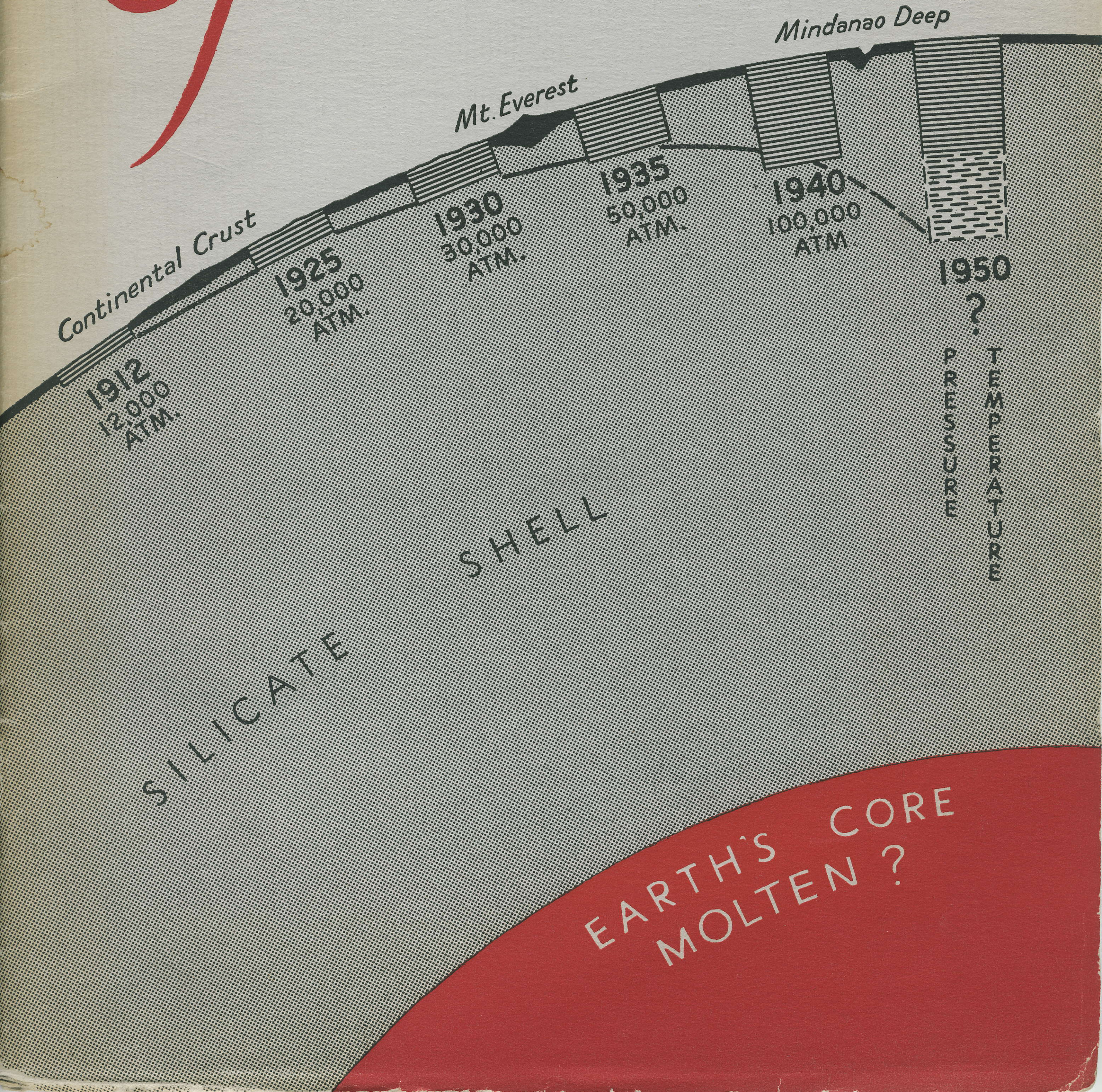
Geophysics at Harvard



Geophysics at Harvard

I

Birth of a Science

MAN lives on the thin crust of a giant cauldron. Poets like to call it the "solid earth." The men whose business it is to look hard at the earth — the geologists — know that the poets are wrong. They know the continents are rock rafts afloat on a thick, world-circling layer of extreme weakness. Leonardo da Vinci's keen eyes long ago saw the truth of sea shells buried high in the mountain side, and he concluded that "the light surface of the earth is continually raised . . . and the ancient beds of the sea become chains of mountains."

The great geologists of history — James Hall and Dana in this country, and the inspired Alpine workers — detailed a story of the contortion of the earth's crust in ages past. Students of earth morphology, climaxed by the late Professor William Morris Davis of Harvard, proved the magnitude of the leveling forces — ice, wind, and running water. Unhindered, these would reduce the surface of the earth to a flat, featureless plain in a few per cent of the earth's historical existence.

The flotation of our vast continental rafts on their weak supporting layer is of such delicacy that when these rafts were loaded by the slight additional burden of ice during the glacial period they were depressed by more than a thousand feet. In the short fragment of geological time since melting of the ice, the return to equilibrium has been almost complete. Most of the well-known surface forces act toward the rapid attainment of an equilibrium state of little change.

What then disturbs this equilibrium? What forces rend the crust with earthquakes, cause the mighty volcanoes to spew their brew over the lands, cast up our great mountain chains? Answers to these questions, now unknown, will one day fill a library of books, and will make men incomparably rich — in raw materials, in philosophy, and in security against natural forces.

When they have looked as hard inside the earth as they have outside, the geologists will know whence come oil and the precious ores, mountain ranges, volcanoes, oceans, earthquakes. They will learn how it is that workable bodies of ores — ores of gold, silver, copper, lead, zinc, nickel, and mercury — have been brought within man's reach by hot solutions. They will find out

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RIVERS OF ICE: *The photograph of an Alaskan glacier (opposite), taken by Bradford Washburn, illustrates graphically a fundamental fact of geophysics — that under great stresses, substances normally considered hard and unyielding, flow like a liquid. Here ice from several separate mountain cirques is flowing, like a giant river, to the sea. Rocks, too, seem brittle and hard to our touch yet, like ice, rocks under the great stresses of the underground, exhibit properties of plastic flow.*

ROCKS BEND AND FLOW: *Surface evidence of the tremendous forces of the earth is found best in mountain cliffs like this 4000-foot cut in the Alps. Here brittle limestone has been folded and pleated by the underground thrusts of mountain building. Geophysicists seek to understand the characteristics of rock which make such flow possible, and, more fundamental still, the nature and origin of underground forces which produce such contortions and are responsible also for earthquakes and the deposit of valued ores within man's reach.*

how tens of millions of tons of ore find their way into surface caches prisoned in solid rock. Then they will know better how to find ores and exploit them. They will discover by what titanic upthrusts mountains are built. They hope ultimately to understand the forces that cause earthquakes, where these forces operate and how, where they may strike next, and how man can best protect his communities against bursts of these underground waves. Because earth and sea and air are bound together by indissoluble chains of interaction, geologists will give new perspectives to oceanography and the science of weather. They will amass the data upon which philosophy is based,—the story of earth's origin and evolution, and its physical future. And from earth they will learn much about the universe beyond.

Such things lie beyond the horizon. Geologists face the immediate, practical problem: how get down into the earth beyond the outer two or three miles where mine and oil-well end, particularly down the fifty outer miles of crust most important to geological processes.

Since no one can go personally into the depths, messengers must be sent down. These are the earthquake waves, waves from naturally occurring shocks, and artificial waves set off by blasts of dynamite. The waves are sent down, to bounce back from various levels. For forty years seismologists have studied the wave forms and have designed instruments of greatest delicacy to record their direction and intensity. In the surface layers, where the nature and conditions of the rock are known, the fast traveling waves have been a sure tool. They reveal oil deposits; they aid in the underground mapping of rock formations; they show that the rock of the ocean beds is much denser than continental rock; they can tell much about the nature of earthquakes.

The wave messengers coming from great depths — those beyond a few miles — need special interpretation. Until this is perfected it is not possible for geologists to decode the waves into messages of earth processes.

As often in the past, when in search of quantitative aid, geology has turned again to physics. It was the English physicist, Cavendish, who, in 1798, took a yardstick and a piece of string to measure the most fundamental of all earth-facts, the gravitational constant, which in turn yields the average density of the earth. In 1864 Lord Kelvin applied equations of heat conductivity to the problems of earth's rate of cooling, and his findings initiated the intensive modern speculation over the age of the earth. In this century, Mme Curie's discovery of radioactivity led to the use of the lead-uranium ratio as the standard determinant of earth-age.

Geology now poses for physics the problem of studying the condition of matter under pressures ranging up to millions of pounds per square inch and temperatures of hundreds or thousands of degrees centigrade. It is a problem that physicists today are prepared to attack. With advancing skill in electrical measurement, in high pressure technique, in analysis of wave forms, in microscopy, in temperature control, and in the theory of models, the physics laboratory is now the natural and indispensable ally of earth science.

The alliance of the two sciences has been named "geophysics," a term which signalizes to physicists a new and intensely practical turn to their studies of matter and to geologists the rebirth of their qualitative science as a potentially great quantitative discipline.

II. Geophysics at Harvard

BECAUSE geophysics demands the coöperative interest of all the earth sciences — geology, physics, meteorology, oceanography, seismology, chemistry, mathematics, astronomy — the large university with laboratories and workers already in these fields, and with easy communications between them, is ideally equipped for the new scientific adventure.

The San Francisco earthquake of 1906 marks an important starting point in the study of geophysics at Harvard. Interest in seismology aroused by this tragedy led an alumnus of the university* to equip the Harvard Department of Geology with two mechanical Bosch-Omori seismographs, which were set up in Cambridge under the supervision of Professor J. B. Woodworth. In the busy University Museum the amazingly sensitive instruments recorded the coming and going of classes, the nightly rounds of the janitor, and the passage of trucks on the streets outside. But for twenty-five years it also kept steady records of deeper-seated earth tremors. Even under the difficult circumstances of observing, Professor Woodworth persevered in his pioneering work. Today with one of the most complete files of seismological records in the world, the Harvard station has been moved beyond the range of city irritations and equipped for recording earthquake waves with accuracy and completeness of the highest order.

Two other main streams, besides seismology, converge into the story of geophysics at Harvard. These are best represented by the names of Reginald A. Daly and P. W. Bridgman.

Professor Daly has studied and taught geology at Harvard for almost forty years, and much of that time has been spent in the far corners of the world, studying the surface clues which have yielded information about the nether earth. In South Africa, Canada, Europe, the Pacific Islands, the Pacific Coast, and New England, he has searched out evidences of volcanic activity, old and new; he has studied the origin of coral reefs; he has studied the changes in sea-beach levels over thousands of years, the metamorphism of rocks, the nature of ores, and of rock-changing gases. He developed new theories about mountain-building; he showed how much the weight of glaciers had distorted the continents. His work enabled the estimation of one of the basic geological facts, the viscosity of the rock substratum fifty or more miles down on which the continents float.

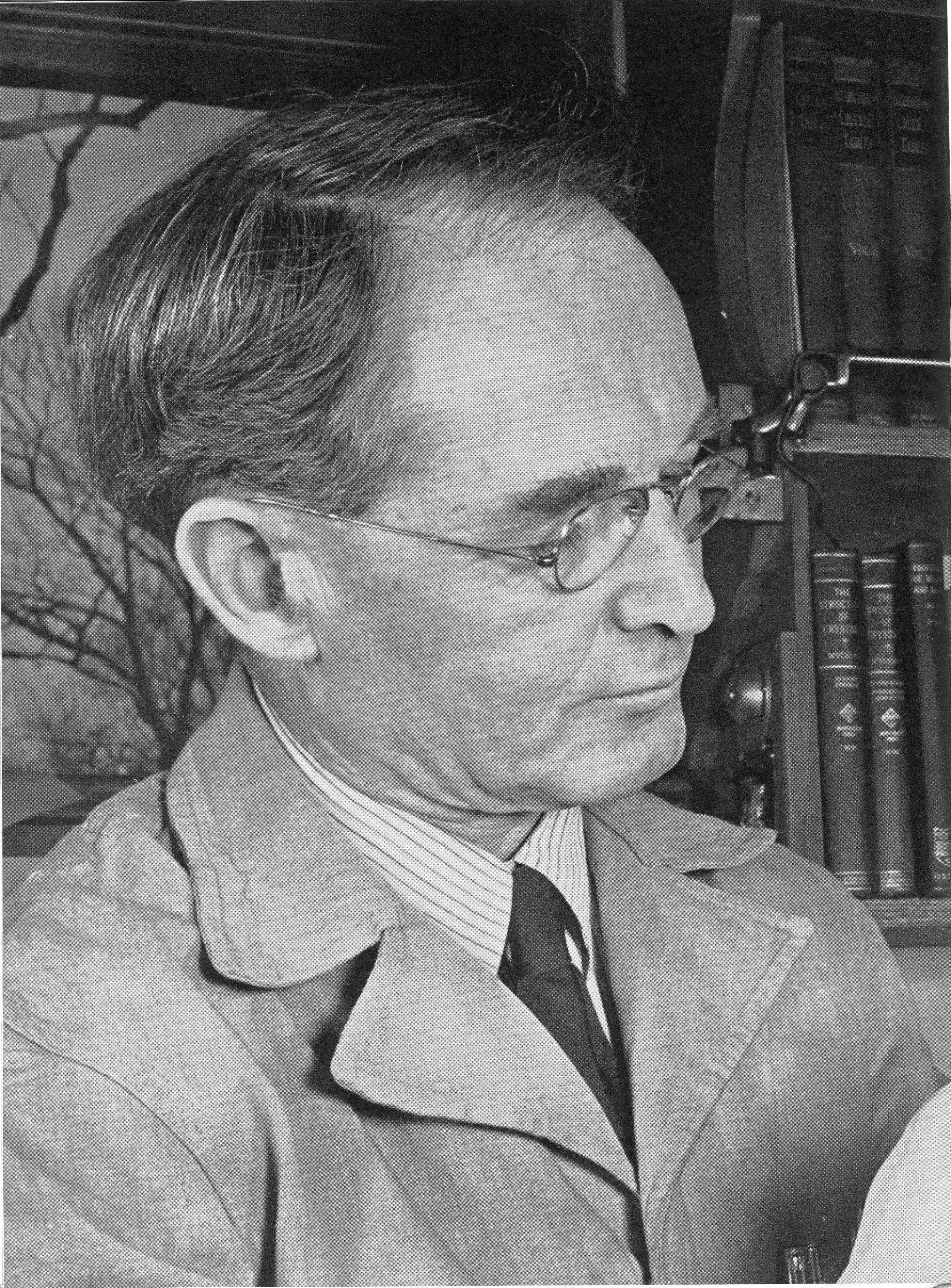
Increasingly, however, he longed for more precise quantitative tools to probe the underground.

Professor Bridgman, meanwhile, wrestled with the problem of harnessing high pressures as a new laboratory instrument for the investigation of the inner structure of matter. When Professor Bridgman began his work thirty years ago, the top limit of controlled pressure for laboratory experimentation was of the order of 5,000 atmospheres, or about 75,000 pounds per square inch. Beyond that it was them impossible to go. Pressure was applied by a hydraulic press, operating through a piston, on material placed in a cylinder. At 5,000 atmospheres, either the piston would break, or the cylinder would explode, or the pressure medium would leak out.

Professor Bridgman had the vision of a stupendous extension of the pressure range, to millions of pounds per square inch, sufficient to wrench and squash particles from their accustomed arrangement, and thus

* Robert W. Sayles '03, Chestnut Hill.

THE GEOLOGIST: *Professor Reginald A. Daly (opposite) has spent his long scientific career studying surface evidence of the titantic underground forces, — volcanoes, changing sea-beach levels, rock metamorphism, ore deposits, and mountain building. His interest in developing experimental tools for quantitative laboratory study of these phenomena led to the birth of the Harvard geophysics program.*



under laboratory torture to make them give up information about themselves.

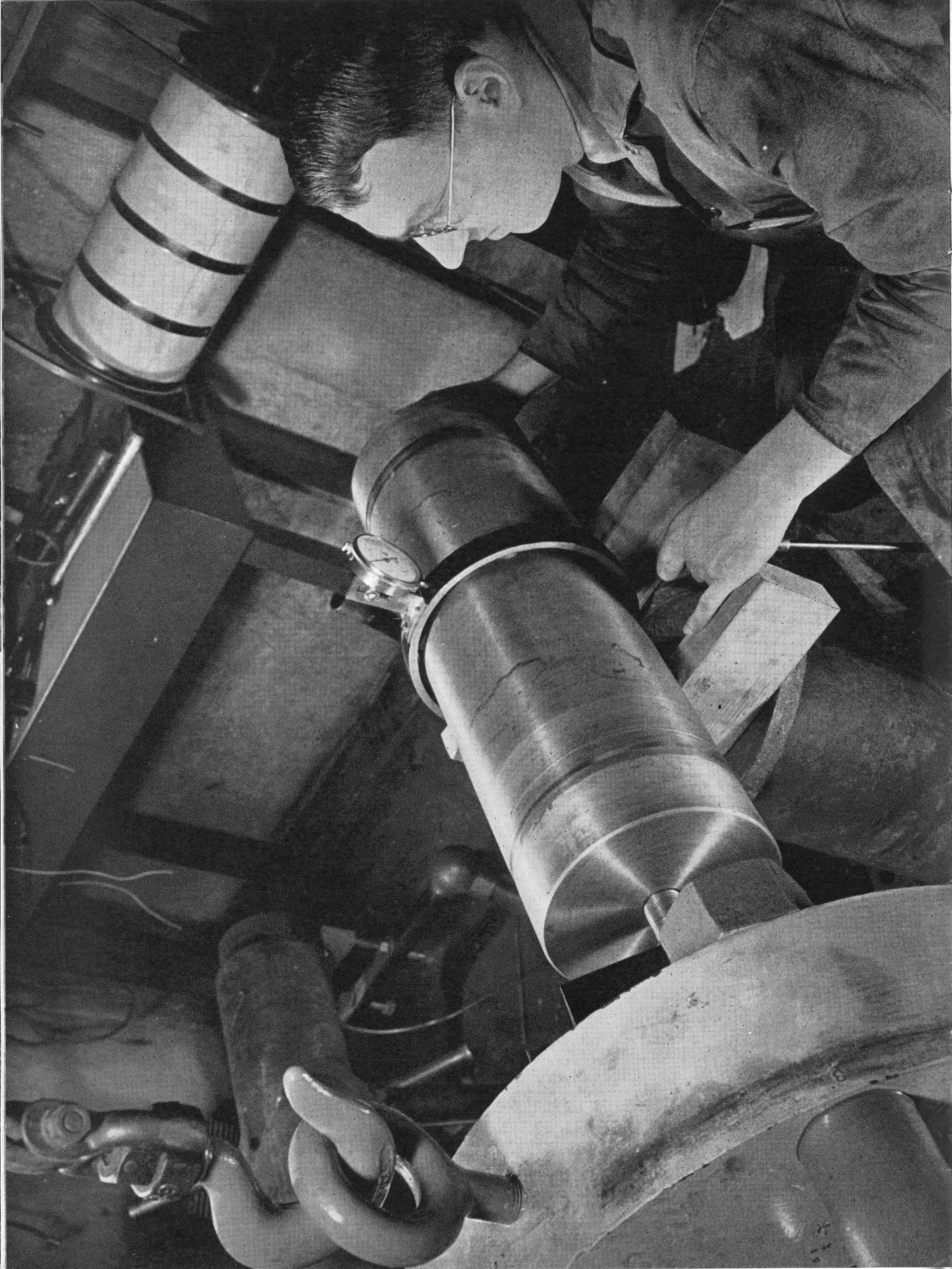
The first problem to be met was that of leakage. Bridgman's solution was fundamental and is in standard use the world over for pressure experiments. Once discovered, the solution is simple, a method whereby the pressure on the packing of the cylinder is kept automatically always higher than the pressure on the material under study. And Professor Bridgman worked the principle into the design of the cylinder in such wise that the experimental pressure does the work of making the packing leak-proof. At highest pressures, the packing washers are of heat-treated alloy steel, which flows under the burden and seals the joints.

Utilizing his new packing principle, and testing out one new steel alloy after another in piston and cylinder, Bridgman, by 1930, had through successive feats of invention reached pressures of 20,000 atmospheres. Alongside the pressure control he developed electrical techniques for making precise physical measurements under the extreme conditions. Results were now pouring in. At the high pressure new forms of ice were formed, with a melting point hotter than boiling water. Other materials studied showed similar basic changes. Professor Bridgman had reason to believe he was on the way to vital new facts about matter.

THE PHYSICIST: *Professor P. W. Bridgman (opposite), master of high pressures, in the past thirty years has extended the range of laboratory-controlled pressures from a top limit of 75,000 pounds per square inch to a new record high of more than 6,000,000 pounds per square inch. His apparatus and the young men trained in his laboratory form the keystone of Harvard's geophysical research.*

Professor Daly thought so, too, but he was thinking not so much about matter in general, as about underground rocks in particular. Here was a tool for making quantitative studies of one of the two primary underearth conditions — enormous pressure. Professor Daly secured Professor Bridgman's interest in the geological aspect of the pressure work. Together with Professor Harlow Shapley, Director of the Astronomical Observatory, Professor G. P. Baxter, of the Chemistry Department, and Professors D. H. McLaughlin and L. C. Graton, geologists, Professors Daly and Bridgman in 1931 formed a committee on geophysical research, organizing an extensive program of research, financed by gifts from the Rockefeller Foundation, the Geological Society of America, and friends of Harvard. Geophysics at Harvard became a conscious, organized, field of investigation.

The first problem before the committee was the selection of a man to guide the development of the program. Clearly Bridgman and Daly were too much occupied with their own work to undertake the task. The future of Geophysics at Harvard depended on finding a man with an unusual combination of talents: he must be able to direct his energies into new channels which would be most productive of important geophysical results; he must be highly trained in a rare field of specialization — classical mathematical physics, elasticity and hydrodynamics; he must be able to work with his hands, to develop high pressure apparatus which would operate at high temperature, and devise means for electrical measurements of great delicacy which would function under these abnormal conditions.



Members of the committee combed the world's laboratories for a man of established reputation who could satisfy these requirements. None could be found. Finally, the decision was made to entrust the project to a young physicist, Dr. Francis Birch, who had just received his Ph.D. at Harvard for work, under Bridgman's direction, which reached a new high in the combination of pressure and temperature. Since 1932, Dr. Birch has been the mainspring of the growing Harvard geophysical program, and much of the work reported in the following pages is the direct result of his leadership.

The geophysical committee has sponsored work which has resulted in the publication of the 69 scientific papers which are listed by title in the appendix to this bulletin. It is appropriate here to describe briefly the facilities for this work.

Professor Birch has equipped his own laboratory in the Dunbar Building. This has operated with the steady aid of one machinist, Mr. Harold Ames, and the assistance of from one to four research physicists on nonpermanent appointments. In all, ten men have collaborated in this work. Under Birch's direction, Dr. Harry Clark has operated a laboratory for the study of thermal conductivity of rocks in the Jefferson Physical Laboratory.

David Griggs, a Junior Fellow in the Harvard Society of Fellows, has pursued a related, but independent line of research. Through the coöperation of Professor Bridgman, the Society of Fellows, and with financial aid from the Geological Society of America, a laboratory for the study of rock flow and fracture under high pressure and temperature has been in operation under Griggs' direction since 1934, in a part of Bridgman's laboratory.

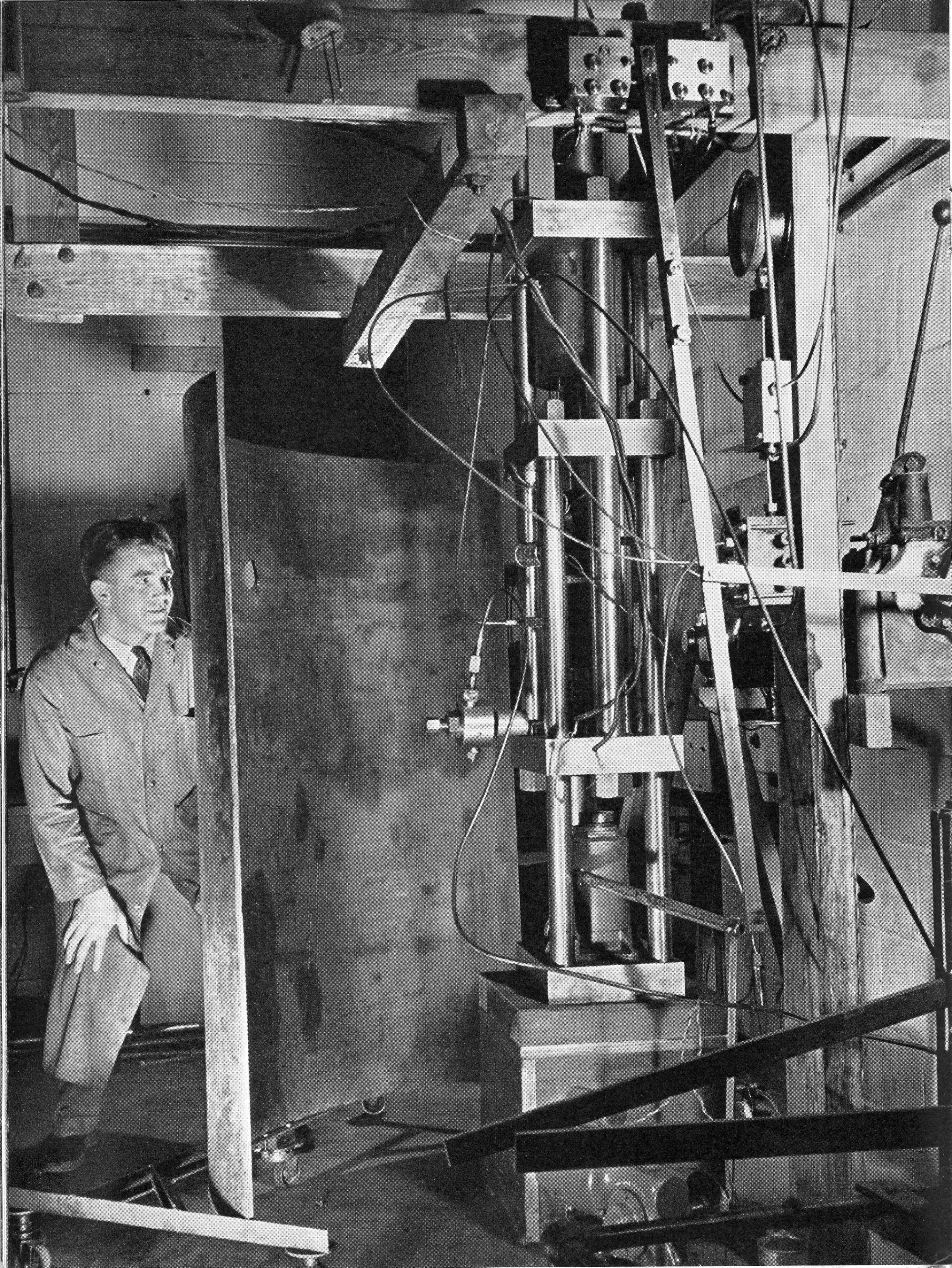
Assistant Professor L. Don Leet has directed the Harvard seismograph station at Oak Ridge since its installation.

Professor Baxter has been actively engaged in Coolidge Memorial Laboratory on problems of molecular weight connected with the study of radiogenic lead and consequent age determinations.

III. Work of Ten Years

THE first decade of intensive geophysical research at Harvard has brought many striking developments. Professor Bridgman reached the colossal pressure of 425,000 atmospheres, or 6,250,000 pounds per square inch. Birch and Ide discovered a method of measuring *directly* the velocity of earthquake waves in rocks under conditions approaching those at depth. Dane measured the viscosity of molten rock under high pressure. Griggs observed flow and fracture in rocks under pressure, and derived the laws

THE GEOPHYSICIST: *Assistant Professor Francis Birch (opposite) was chosen in 1932 to take charge of the new Harvard geophysics research program. His central responsibility has been the extension of Bridgman's pressure methods to embrace the complicating underground conditions of high temperature, chemical solution, and earthquake wave motion. Here Dr. Birch is strengthening a new experimental cylinder by the application of high pressure. This process, one of Bridgman's discoveries, has been adopted by the Army and Navy for large guns.*

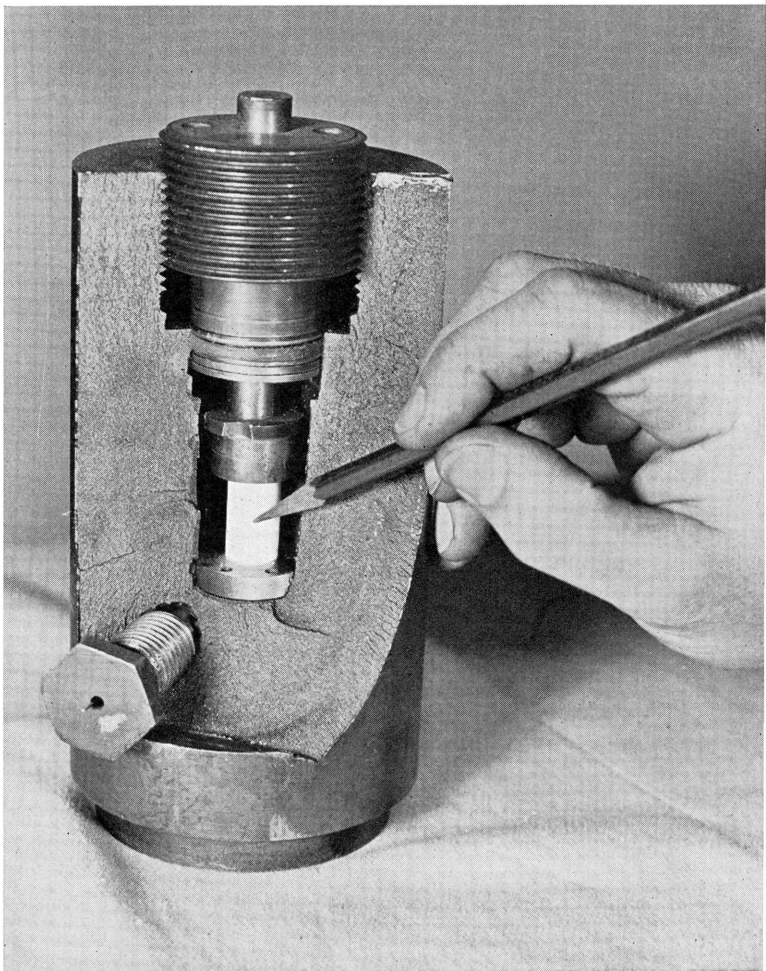


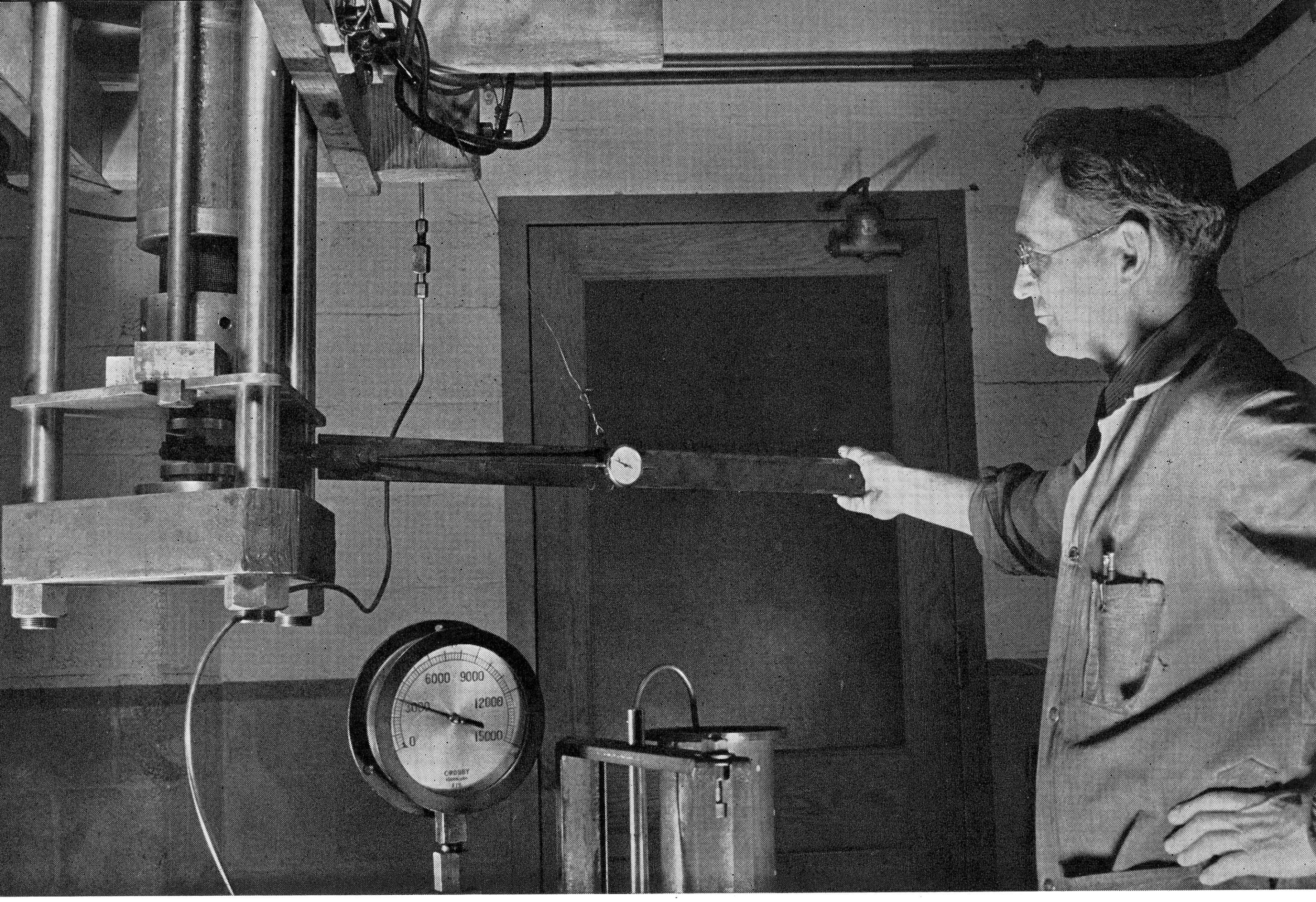
of elastico-viscous flow believed to apply to solid flow of rocks in general. Leet equipped the best seismograph station in the western hemisphere; made Harvard the center for New England seismological information; discovered a hitherto unsuspected form of earthquake wave; and now suggests a new theory of earthquake origin.

Perhaps the most dramatic fact of Harvard's decade of geophysics is Professor Bridgman's extension of laboratory pressure researches from the level of 20,000 atmospheres to the new high of 425,000 atmospheres. With this tool geophysicists are enabled to duplicate pressure conditions down to 500 or 600 miles below ground. Applying the tool himself, Professor Bridgman has established the principle that, under the high pressures, most elements and compounds undergo what are called polymorphic transitions, that is, changes in crystal structure which do not affect the chemical composition. And accompanying the polymorphic transitions are changes in physical properties, among them, significantly for geophysics, a change in density. As a by-product, appreciated by citizens of the twentieth century, Professor Bridgman's efforts to strengthen steel for his pistons and cylinders has led to a new method for toughening the barrels of military cannon. This method of "autofrettage" is now widely used on large guns by both the Army and the Navy.

The next advance in pressure work came when metallurgists developed carboloy, or cemented tungsten carbide, found to have almost double the strength of the best steel then known. Carboloy was put to use in the pressure pistons. Carboloy pistons raised the problem of increasing the strength of the cylinder proportionately. Professor Bridgman conceived the fundamental plan of making the cylinder and its enclosing sleeve in the form of a cone. As the cylin-

CYLINDERS SOMETIMES EXPLODE: *In this apparatus (opposite) rocks are tortured by underground conditions; they are surrounded by a liquid under high pressure, and then a differential force is added, squeezing, pulling, or shearing the specimen. Normally brittle and strong, rocks change their properties in this torture chamber and become plastic and flow, just as hard rocks are known to flow in nature. Protecting shields, such as the one shown here, are necessary in all high pressure experiments, since the steel cylinders are stressed near the breaking point and sometimes let go, in an explosive rupture. The high temperatures of geophysical experiments add to the danger of explosions. An example of a ruptured cylinder is shown (right). It is not surprising that the best steel cylinders fail, because Bridgman's common working pressure is about fifteen times that inside guns.*





THIS PRESS BROUGHT A NEW WORLD RECORD: *This is a shearing apparatus used for exploratory measurements at very high pressures, and is one of many types of high-pressure equipment devised by Professor Bridgman. Work with this press led to the attainment of a new world-record experimental pressure — 425,000 atmospheres, or 6,250,000 pounds per square inch.*

der was pressed into the coned sleeve, a strong confining pressure would develop. With the cone principle, Professor Bridgman doubled the strength of the cylinders. The pressure range was now brought to 50,000 atmospheres.

In Bridgman's laboratory, David Griggs, working in the geophysical program on the effect of high pressures on rocks, found the clue for the next surge forward in pressures. He discovered that a liquid confining pressure greatly increased the strength of rocks, sometimes ten-fold. This finding reopened the question of reaching extreme pressures by a cascade of apparatus, in which a small ultra-high pressure chamber would be completely surrounded by liquid under high pressure. It had been thought that the cascade, with all its experimental difficulties, might at best simply double the strength of the inner cylinder. Mr. Griggs' work made it appear that the inner cylinder strength might increase exponentially with confining pressure.

It remained for Professor Bridgman to resolve a difficult dilemma of the cascade equipment. The initial problem is to maintain the confining liquid pressure constant while pushing on the piston of the inner cylinder. Previous methods had always relied on two coupled pistons in the outer large cylinder to maintain the confining pressure constant. In the cone-shaped cylinder, however, this older method utilizes all the available openings, leaving no room for the insertion of electric leads for measurement of the physical events in the inner chamber. Professor Bridgman's solution utilized an earlier finding of his own that in a number of elements when polymorphic changes in crystal structure occurred, there was a corresponding change in volume at constant pressure. It proved possible to utilize this fact of volume change to maintain confining pressure automatically constant at a fixed value. Bismuth is now used to maintain a constant pressure of 25,000 atmospheres around the inner cylinder. With the new cascade apparatus, experimental pressures of 100,000 atmospheres are workaday, and the colossal pressure of 425,000 atmospheres has been attained.

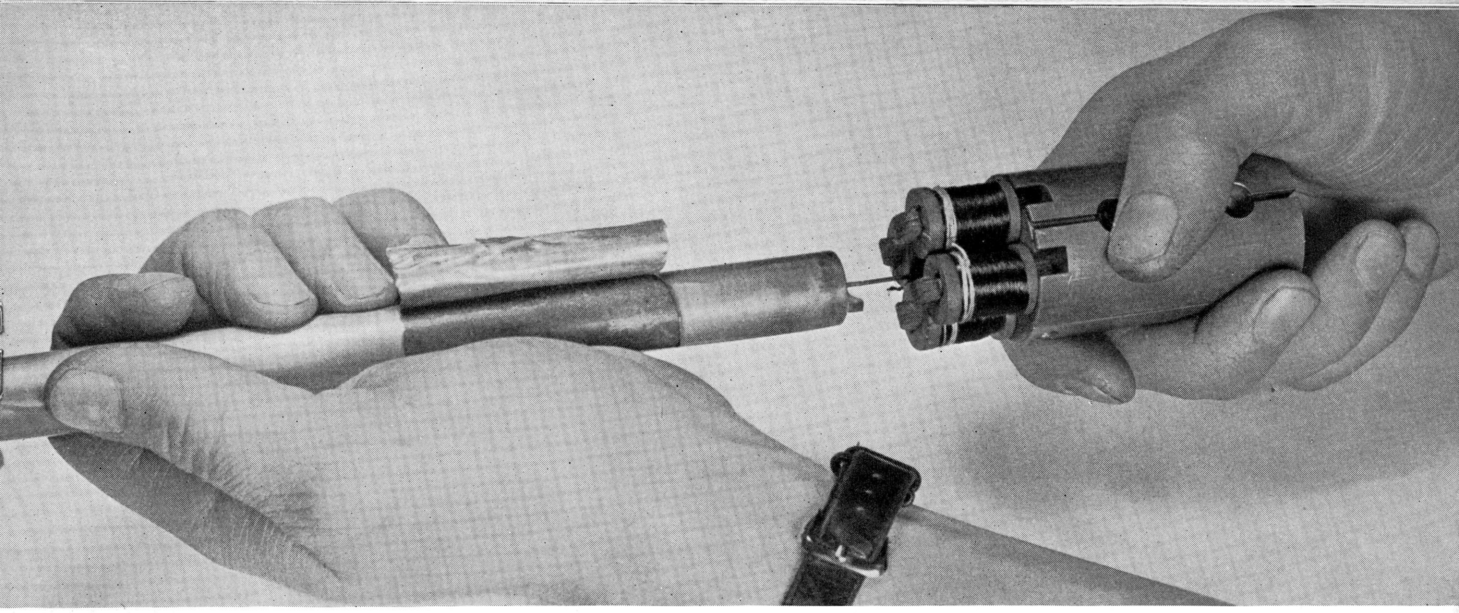
Hand-in-hand with the effort for higher and still higher pressures has gone the study of the polymorphic transitions of hundreds of materials. Seven different forms of ice have now been found, each with different crystal properties. The highest pressure form, Ice VII, does not melt until heated above 370° Fahrenheit. The viscosity of some substances was found to increase more than a million-fold under high pressure. Some permanent changes are induced which persist even after removal of the pressures. Thus black phosphorus can be formed only at high pressure, but will remain in that form indefinitely after release. Hundreds of materials have been subjected to the cylinder torture chambers, and roughly half of them have shown the polymorphic, crystal changes.

These researches have dealt with the properties of matter under hydrostatic or liquid confining pressure pressing in upon the subject material with equal stress from all sides. However, long before, Professor Bridgman had theoretically deduced that shearing stress would also have important effects in changing the state of materials. About 1934 he first made the attempt to use this effect of "differential" pressure as a new exploratory tool in the field of extreme pressures. Of utmost simplicity in design, his new apparatus may be assembled, used in a test run through a range of zero pressure to 50,000 atmospheres, and disassembled all in the space of half an hour.

With this "shearing apparatus" dozens of new polymorphic transitions have been discovered. Spectacular chemical changes have been induced which would not occur otherwise at room temperature. Some of these occur with explosive rapidity. It is not an uncommon experience for Professor Bridgman's neighbors in Jefferson Laboratory to hear a sharp detonation as though a rifle had been discharged. Any one obeying the natural impulse to rush in and pick up the pieces is usually greeted by Professor Bridgman's smile of satisfaction at the discovery of a new chemical "detonation" in the shearing apparatus.

This apparatus, too, yields much of geophysical value. Many materials, it has been found, will fracture under the extreme shearing stress, but will re-heal themselves immediately because of the high confining pressure. Here is a clue, perhaps, to the mechanism of deep-focus earthquakes. The paradox of earthquakes in material at

EARTHQUAKE WAVES IN THE LABORATORY: *Measured velocity and forms of earthquake waves give clues to the materials through which they pass. Equipment developed at Harvard enables the direct laboratory measurement of velocities in small rock samples. Above Dr. Birch applies pressure magnified by the overhead press to several thousand atmospheres, equivalent to natural pressure at 10 or 20 miles underground.*



LABORATORY WAVES IN ROCK SPECIMENS: *Detailed picture of the apparatus by which it is possible to produce vibrations in rock specimens similar to natural earthquake waves of various types, and to measure with precision the velocity of wave-transmission in various rock forms. By electric means, torsional vibrations are applied to one end of the specimen and received at the other end. Determination of the resonant frequency of the specimen gives directly the velocity of the waves in the rock under study. Since we have records of the velocity of earthquake waves underground, these laboratory measurements give an approach to determination of the composition of the rocks traversed by the natural waves. Here in the left hand is a rock cylinder, with its enclosing jacket of foil partly ripped off. In the right hand is the electrical mechanism which induces the vibrations in the rock.*

depth known to be weak and yielding has long puzzled geophysicists. Although we know that the rocks at depth will yield continuously under shearing stress, it is not impossible that this yield occurs in steps marked by rupture and subsequent rehealing.

In collaboration with Professor Esper S. Larsen of the Department of Mineralogy, Professor Bridgman has investigated the effect of extreme shearing on many mineral mixtures of geological importance. The experiments did not succeed in duplicating underground metamorphic changes, but they did reproduce the orientation of minerals in many cases similar to that produced in rocks subject to extreme shear in nature—schists, gneisses, etc.

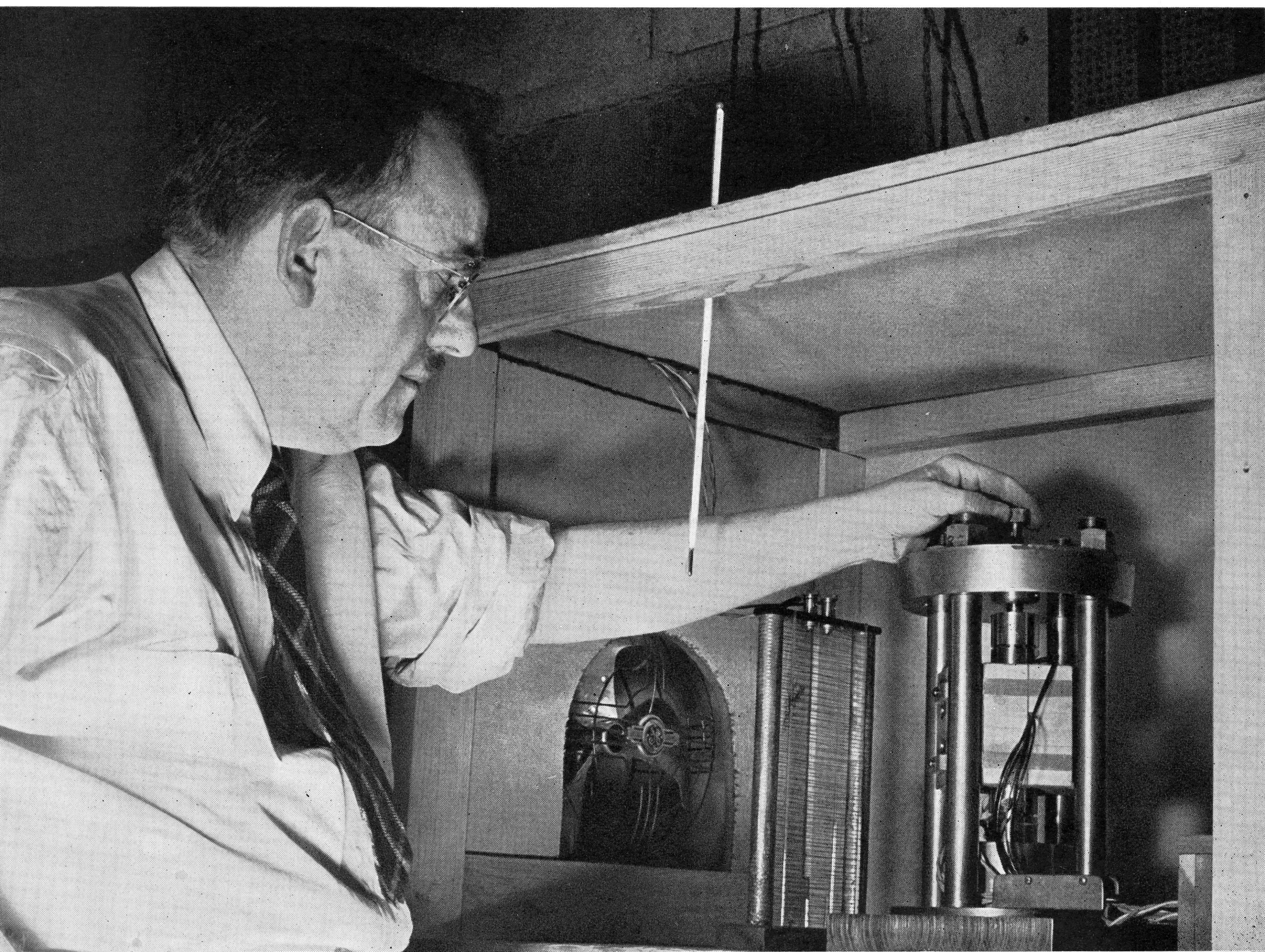
One of the first researches in the geophysical program was an effort to throw light upon the confusing situation which then existed with respect to the elasticity of rocks. This work, essentially an application of engineering methods of testing with very sensitive apparatus, was carried out by Dr. W. A. Zisman; it showed the very great dependence of the elasticity of rocks upon the amount and kind of stress used in making the measurements, and it constitutes an important link between the ordinary variety of test and the subsequent investigations at high pressures.

The extension of Professor Bridgman's methods to embrace the underground conditions of high pressure and chemical solution, and to measure the important factors of rock elasticity, has been the responsibility of Dr. Birch. Not the least of his difficulties and those of his colleagues has been the fact that application of heat and chemical solutions in the pressure chambers greatly increases the chances of equipment explosion. The new geophysics research program was exiled to the Gordon McKay Building, at a safe distance from the rest of the physics laboratories.

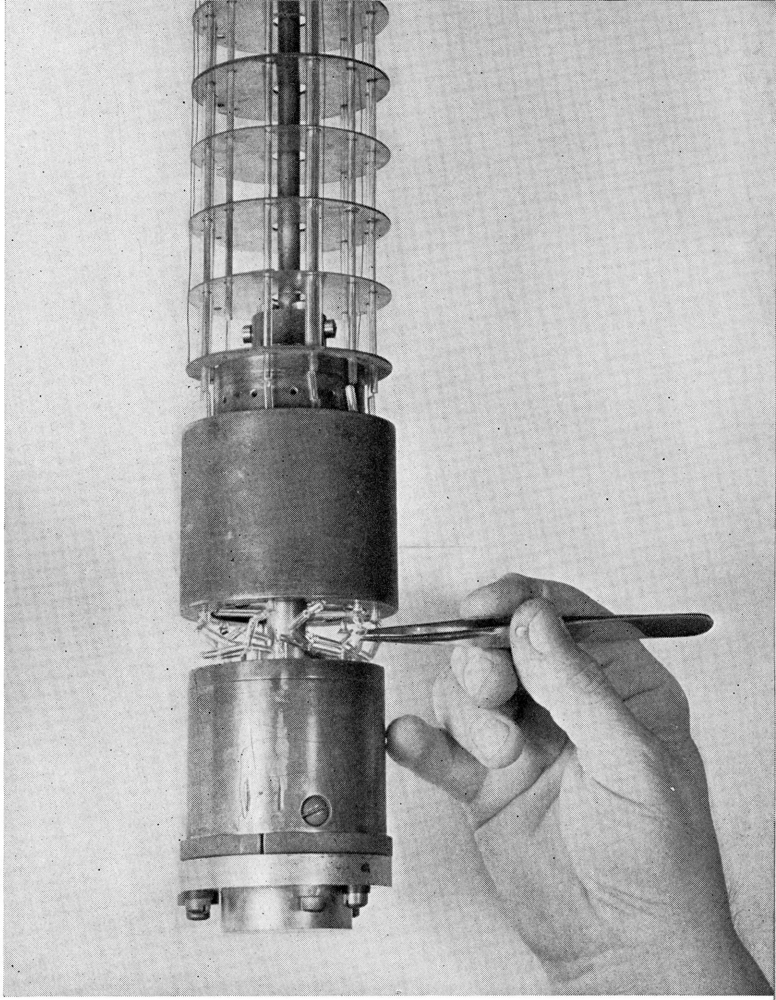
In a series of experiments, Dr. Birch and his associates have begun to piece together the laboratory information needed for interpreting the seismologist's wave-signals. The problem, in simplest terms, was to determine in the laboratory the velocity of earthquake waves in certain rocks under conditions of high pressure and temperature. Armed with such data, the seismologist would be able to examine his records of underearth wave velocities with increasing certainty about the nature of the material through which the waves were passing.

Dr. Birch began his work with an attempt to develop the classical method of theoretically calculating the wave velocities from knowledge of the compressibility of rocks. He designed new apparatus for measuring the volume changes of rock under the combined underground conditions of high temperature and high pressure.

HEAT CONDUCTIVITY — CLUE TO MOUNTAIN BUILDING: *The earth's heat is the only known source of energy great enough to wrinkle its face. The primary clue to earth heat is knowledge of the thermal conductivity of rocks under subterranean conditions. Dr. Harry Clark has designed special apparatus to measure the absolute conductivity of rocks, and his measurements on many different rock types fill one of the largest gaps in geophysical data.*



HEART OF THE HEAT-CONDUCTIVITY APPARATUS: *Enclosed in massive blocks of pure copper (right) are the rock specimens under study and the necessary delicate platinum thermocouples. Perhaps the greatest difficulty of the heat-conductivity experiments is the length of time required to reach equilibrium before each measurement. The experimenter must reconcile himself to hours of patient waiting for each observation.*

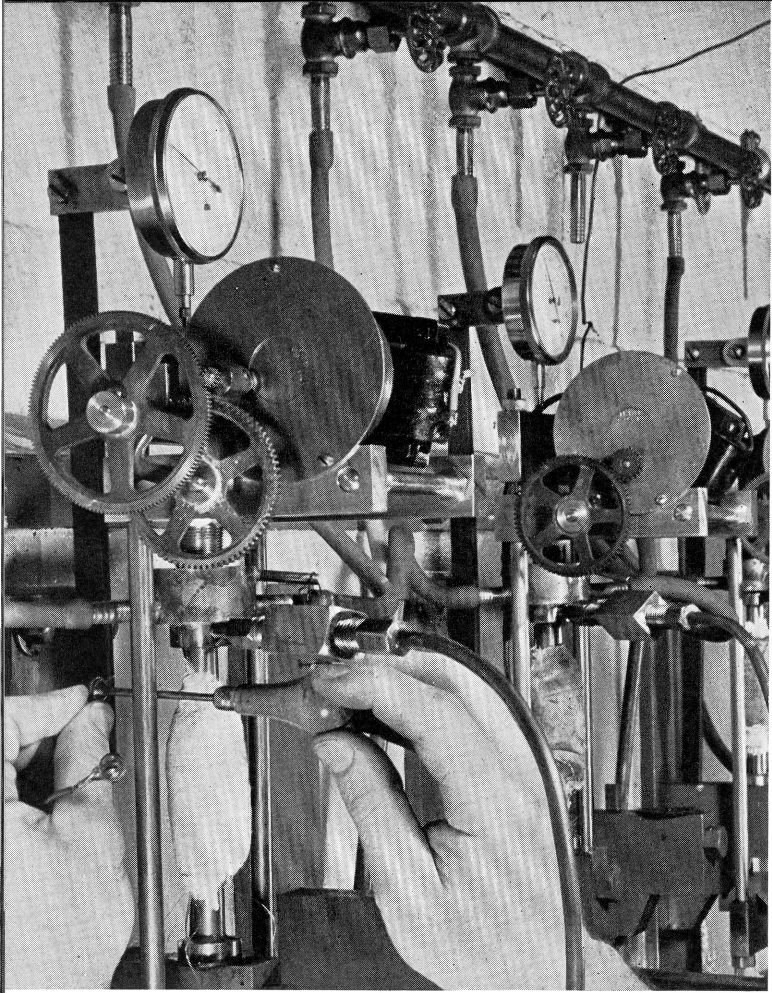


Painstaking studies yielded a series of standard tables on rock compressibility. A major hurdle, however, barred progress toward the extremely accurate calculation of the wave velocities which Dr. Birch sought to achieve. Wave velocities can be calculated from compressibility only indirectly and with a sacrifice in accuracy. To achieve accuracy commensurate with the compressibility measurements, it was necessary to measure one more of the elastic constants, and this imposed serious experimental difficulties.

As Dr. Birch wrestled with the problem of more accurate measurements of elasticity, Dr. J. M. Ide, from the laboratory of communication engineering, came forward with an entirely new method for measuring *directly* in the laboratory the velocity of earthquake-type waves in rock specimens. Basically, the Ide method measures wave velocities in rock specimens by subjecting the specimens to rapid vibrations and discovering the point at which resonance occurs. Many measurements were secured for the velocity of waves in rocks at room temperatures and atmospheric pressure.

Later work has been directed toward the adaptation of these methods for investigations at successively higher pressures and temperatures, and toward the accumulation of a substantial mass of data. Currently the apparatus has been developed to realize conditions at a depth in the earth of about twenty miles, where the temperature is thought to correspond to a bright red heat. Comparison with earthquake data shows that these experiments have succeeded in reproducing with considerable fidelity the conditions of propagation of real earthquake waves, where small periodic stresses are transmitted through material under enormous pressure and temperature. In future detailed comparison of such laboratory measurements with the velocities recorded by the seismologist lies the hope of ultimate recognition of the nature of the earth's crust.

Because some of the earth's shells are



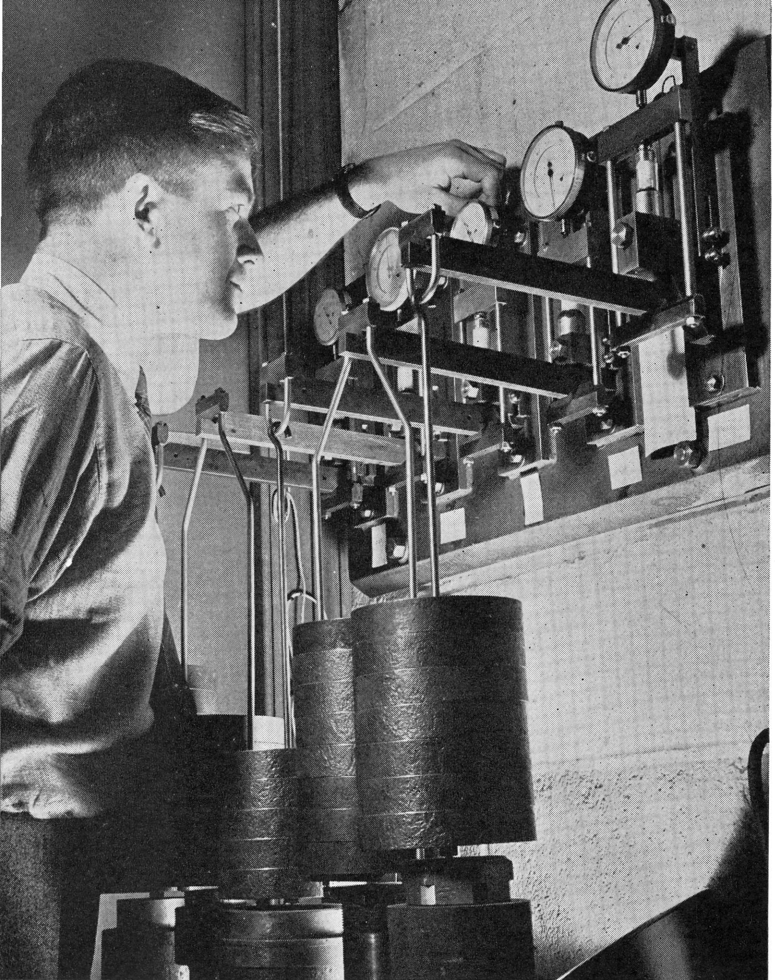
CREEP OF ROCKS: *It is necessary to have many duplicate sets of apparatus for creep tests since each experiment may last for a long period of time. In this investigation of creep of rocks, some specimens have been under constant pressure for years. In the apparatus at the left, liquid under constant pressure is supplied through the curved pipe to the cylinder, which is surrounded by the white furnace. Squeezing pressure is applied to the specimen by a load applied to the yoke. The piston is rotated constantly by the geared motor to apply shearing stress. Deformation of the specimen is measured by the dial gauge to an accuracy of one hundred-thousandth of an inch. The battery of creep testers (right, opposite) measures the deformation of rocks under low stresses applied for a long time. In this apparatus it has been possible for the first time to duplicate in moderate degree all the variables of the metamorphic environment in nature: pressure temperature, shear stress, mineralizing solutions — all acting over long periods of time. It is now possible to reproduce some of nature's metamorphism. Thus, sand can be recrystallized into hard quartzite.*

probably too hot to be crystalline, and hence may be virtreous or glassy, it is a laboratory problem of high order to discover how the viscosity of vitreous materials is affected by the enormous pressures of the underground. With the help of Dr. Birch, Dr. E. B. Dane, Jr., developed apparatus to study the viscosity of a vitreous substance, borate glass, under pressures of several thousands of atmospheres and at high temperatures. The findings show that the viscosity increases noticeably even under very moderate pressures.

With interest in the problem of earth magnetism, Dr. Birch measured the phase change in iron under high pressure and temperature. One of the prevalent theories of the earth's magnetic field is that it is due to ferro-magnetism of an iron-nickel core. Iron changes its crystal form at 910° C., and only the low-temperature form is magnetic. Dr. Birch found that the temperature of this phase-change *decreased* with pressure, so that pure iron could not exist in the magnetic form below a depth of twenty-five miles.

Dr. Manson Benedict and Dr. Norman Keevil have carried on the important quantitative study of volatile solutions under high pressure and temperatures. Basically this is an investigation into the nature and energy of lavas and the origin of ore deposits. The problem of research is difficult, involving analysis of liquid and gaseous phases of the underground melts.

Earth heat is perhaps the most important unknown of geophysics. For one thing, heat is the only known energy source

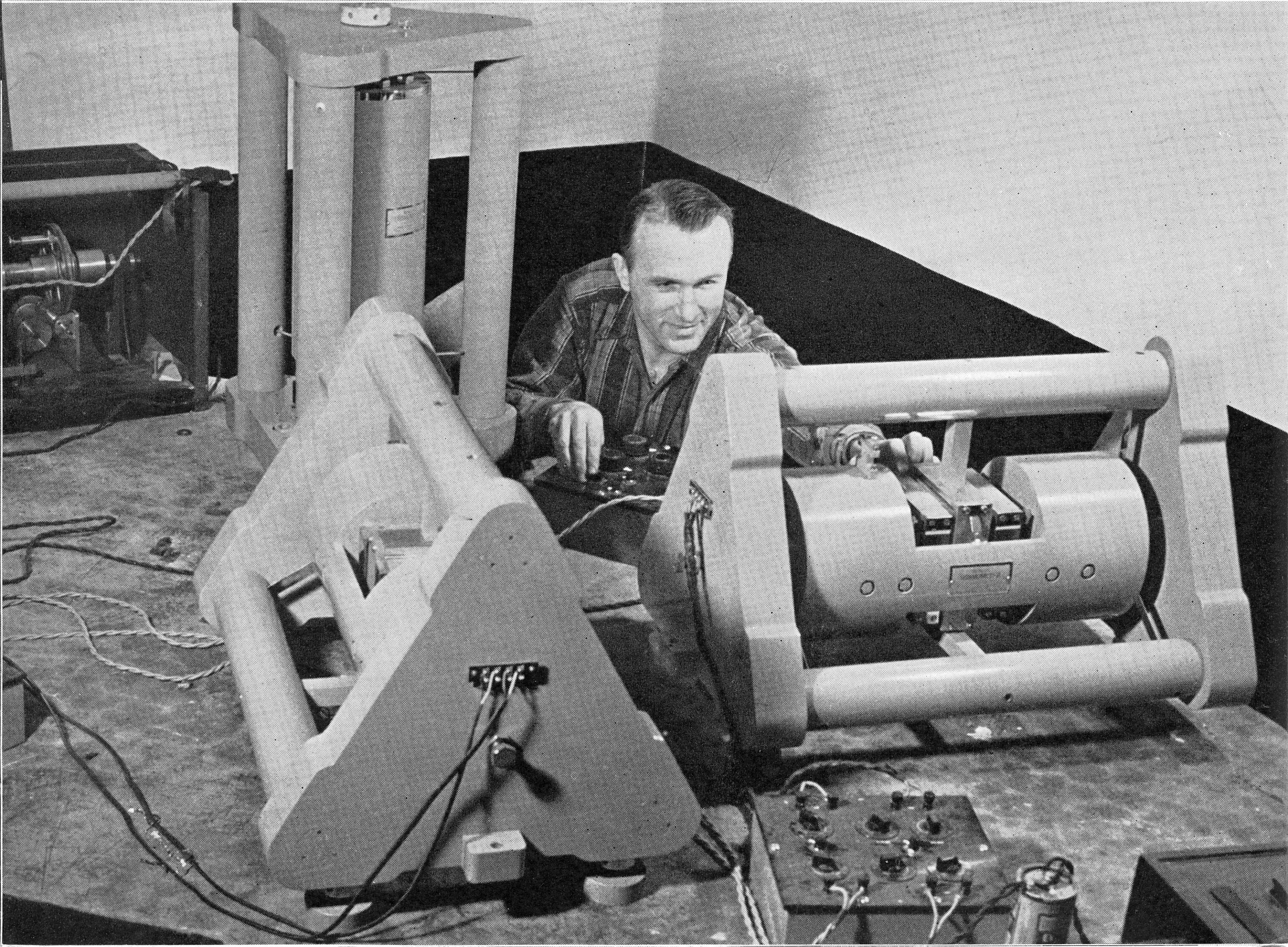


ROCKS FLOW BY RECRYSTALLIZATION: *In the experiments shown at the left it was demonstrated for the first time that rocks actually flow by a process of solution and recrystallization. Since alabaster is the most soluble of rocks, it was chosen for these trials. One may see the specimens of alabaster (white) surrounded by a small jacket of water. They are under constant load supplied by the weights in the foreground, and their shortening is measured accurately by the dial gauges. The specimen in the center, under the lightest load, is still flowing slowly after 900 days. The others have broken, giving us new laws of fracture as well as flow.*

sufficiently potent to contort the earth's face with upthrust mountains. It is, therefore, important to geophysicists to know how rocks conduct heat. Down two miles or so, the temperature can be measured from specially designed thermometers sunk in bore holes. Below that the estimates depend upon knowledge of the dominant rock forms. Dr. Clark has worked on this problem for seven years. In delicate, time-consuming tests, he and Dr. Birch have measured the changes of thermal conductivity of standard rock types at temperatures ranging up to 450° Centigrade. The investigations have resulted in systematizing knowledge of the conductivity of igneous rocks, so that it is now possible to determine the conductivity of any rock from the mineral composition alone. At present this work is being extended to enable measurement of heat-conductivity of rocks under the underground environmental conditions of stress and moisture.

Rocks themselves are not so unyielding as they look. It takes a lot of pressure to do it, but solid rocks can be folded like a soft metal: they are bent up into mountains, and their elastic rebounds cause earthquakes. The deformation of rocks is, in truth, an underground routine. David Griggs has

THE BLACK HOLE OF OAK RIDGE (*opposite*): *The instrument vault of the Harvard Seismograph Station at Oak Ridge, Massachusetts, is a room twenty-two feet square and ten feet high, blasted from solid rock and buried under fifteen feet of earth. In the old days the Harvard seismographs stood in the University Museum, in Cambridge, and their recording of the earth's vibrations was interspersed with records of the coming and going of students in the building, the rounds of the night watchman, and the flow of Cambridge street traffic. In the Oak Ridge station are now housed three Benioff seismometers, two tiltmeters, chronometers, and recording drums, — the finest battery of seismological equipment in the world.*



undertaken to study the facts of rock deformation. He has developed apparatus with which to observe the contortions of rocks under simulated natural conditions of high pressure, high temperature, high shearing stress, and in the presence of mineralizing solutions. Many strong and brittle rocks, he has found, become plastic under the application of high pressure alone, and can be distorted thus into almost any form, and still remain solid and unbroken. Many other rocks will not respond in this way. In these

IN THE FIELD — ARTIFICIAL EARTHQUAKES: *Large quarry blasts send out waves which are very similar to earthquake waves. Since the point of origin and the time of the dynamite blasts are known accurately, the seismologist may use their waves to determine the characteristics of earthquake transmission in near-surface rocks. Small portable seismometers like this one developed by Dr. L. Don Leet, Director of the Harvard Seismograph Station (above, opposite), are placed at critical points around the quarry blast. From the records, much may be learned of the composition and structure of the outer layers of the earth.*

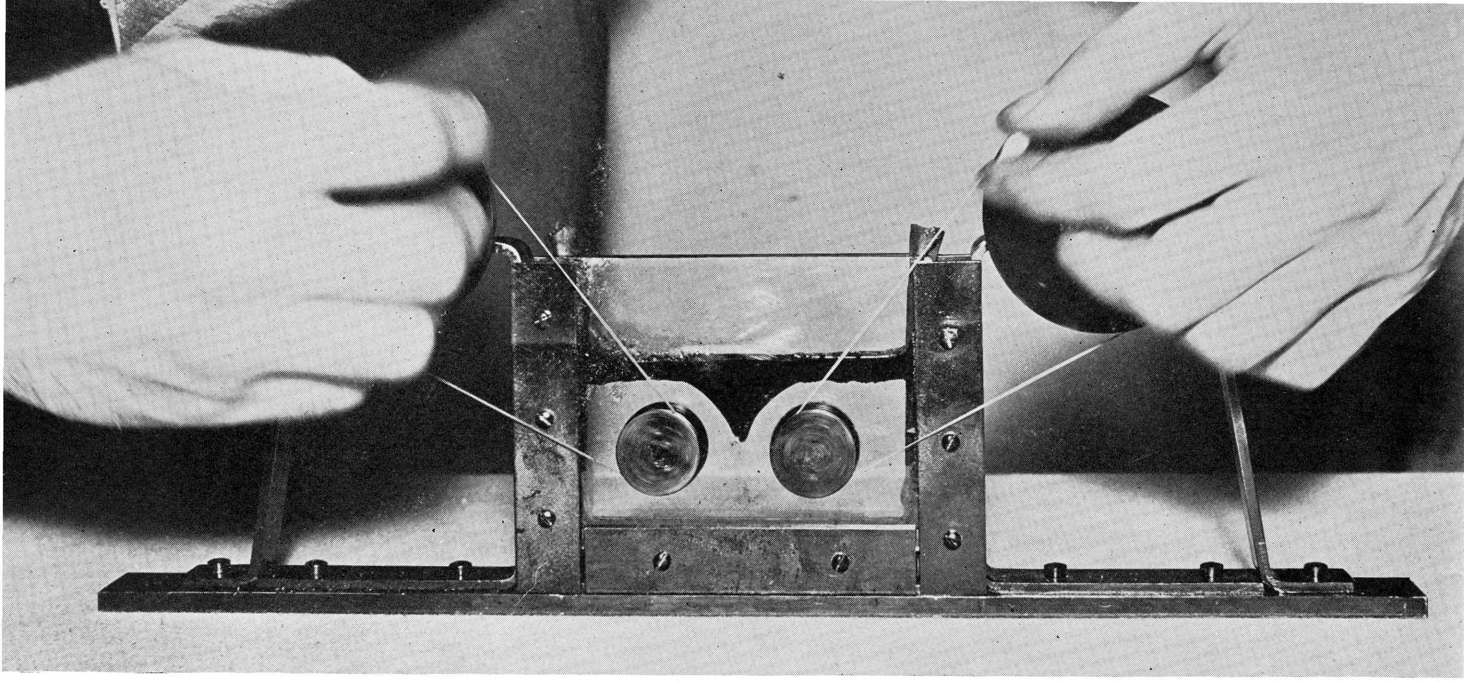
IN THE VAULT: *Most sensitive earthquake recorder in the world is the Benioff seismograph, a development of the last few years. Harvard was the first institution to install a complete battery of three Benioff instruments. Each of the three separate seismometers shown opposite, below, records the motion of the earth in one of three mutually perpendicular directions. From the assembled records it is possible to describe completely the motion of the bedrock during the passing of an earthquake wave. Besides valuable routine records of earthquake events the world over, this battery is of prime use in research on earthquake wave forms. With this equipment Dr. Leet recently discovered a new type of earthquake wave of importance to study of earthquake genesis and wave transmission.*

cases, however, with the application of the other underground conditions of heat, shearing stress, and mineralizing solutions, the rocks lose their quality of strength and become very weak. They flow continually by a process of solution and recrystallizations, a type of flow evidenced by many geological deformations.

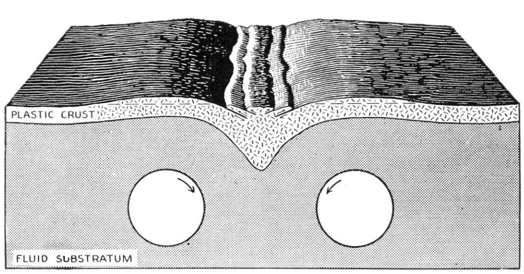
The instruments with which Harvard geophysicists keep in touch with the actual underground, the seismographs, have since 1933 been located at a special observatory on Oak Ridge, in the town of Harvard, Mass., some twenty-five miles removed from the disturbances in Cambridge. Development of the seismograph station was Harvard's first responsibility under the Rockefeller grant, and the work has been carried out under the direction of Dr. Leet. The equipment has been designed to fulfill the three-fold function of modern seismology: the registration and location of some 600 earthquakes a year the world over; analysis of earthquake violence, for the design of shock-proof structures; and analysis of complex underground wave forms for the advancement of geological knowledge.

Development of the station has more than a remote, academic interest for New Englanders today. The records of earthquakes in this area since 1850 indicate that northeastern America is in a period of increasing earthquake activity, which may well result in severe shocks.

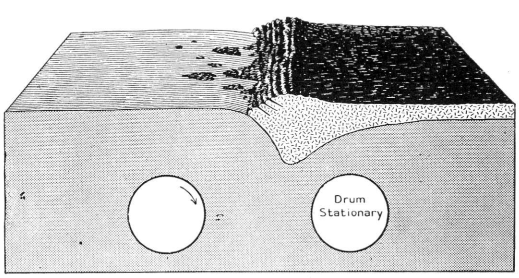
In a vault fifteen feet underground, blasted out of solid rock, Dr. Leet installed the first complete set of the world's most sensitive seismographs, developed by Dr. Hugo Benioff, of the California Institute of Technology. A battery of portable instru-



SCALE MODELS REPRODUCE EARTH PROCESSES: *Many natural processes are too involved to yield readily to mathematical analysis. In these cases, knowledge of model theory enables the construction of accurate scale models. Here is a model which simulates the action of sub-crustal convection currents in the earth. The continental material (black) and the substratum material (clear) are chosen to have the strength and viscosity commensurate with their reduced size. The rotating drums produce currents which are similar to convection currents believed to exist in the substratum. The resultant downfolding of the continental material may be seen in the photograph.*



CONVECTION CURRENTS MAY CAUSE MOUNTAIN BUILDING: *Models show the reaction of the crust to substratum currents. The folding and thrusting which occurs in the model crust is strikingly similar to that in mountain chains. While the currents are acting, the crust is pulled down. When the currents cease, at the end of the convection cycle, the thickened crust rises buoyantly, producing the mountain massifs. In nature the mountain masses are then sculptured by glaciers into their present picturesque forms.*



CURRENTS MAY SWEEP THE CONTINENTAL MATERIAL OFF THE OCEANS: *When only one convection cell operates, it may carry the crust along with it, thickening it and building mountains at the point where it dives to the depths. This may partially explain the existence of continents and oceans. We know that the most recent mountain building occurred in a zone around the Pacific Ocean. Continental material is thickest on the ocean border, but there is none over the ocean basin itself.*

ments for field observations was assembled. It was discovered early that the Benioff instruments gave good records of vibrations from distant dynamite blasts. Dr. Leet launched a program of utilizing such blasts as artificial earthquakes, of known size, time, and place of occurrence. One result of this work was the precise measurement of the velocity of earthquake waves under New England. A second result was the mapping out of three distinct layers below the New England earth surface. The top layer, nine miles thick, is granitic; a second layer, six miles thick, is heavier, probably basaltic; a third layer, six miles thick, is of undetermined composition.

With a portable instrument of his own design Dr. Leet studied the nature of earthquake waves near the source of blasts. A major result of this work was the discovery of a new basic type of earthquake wave, the first to be discovered in 40 years. Velocities of the waves were studied in particular rock areas, and the results were checked against laboratory findings by Dr. Birch. An immediate practical effect of the field studies has been revision of certain seismograph methods of prospecting for oil.

IV. Through the Curtain of the Future

FROM the deliberations of scientific meetings come the harbingers of new developments. This year geophysicists assembled for the second annual assembly of the Section of Tectonophysics of the American Geophysical Union. Tectonophysics, or the physical study of the architecture of the earth, became an organized separate section of the Union last year, taking its place alongside the other geophysical sciences, — seismology, geodesy, volcanology, oceanography, terrestrial magnetism and electricity, meteorology, and hydrology. Harvard geophysics is strongest in the field of tectonophysics, and the papers of the Harvard group at the meeting of their section this spring served to illustrate graphically the relation between Harvard laboratory developments of the past ten years and future progress in geophysics and geology.

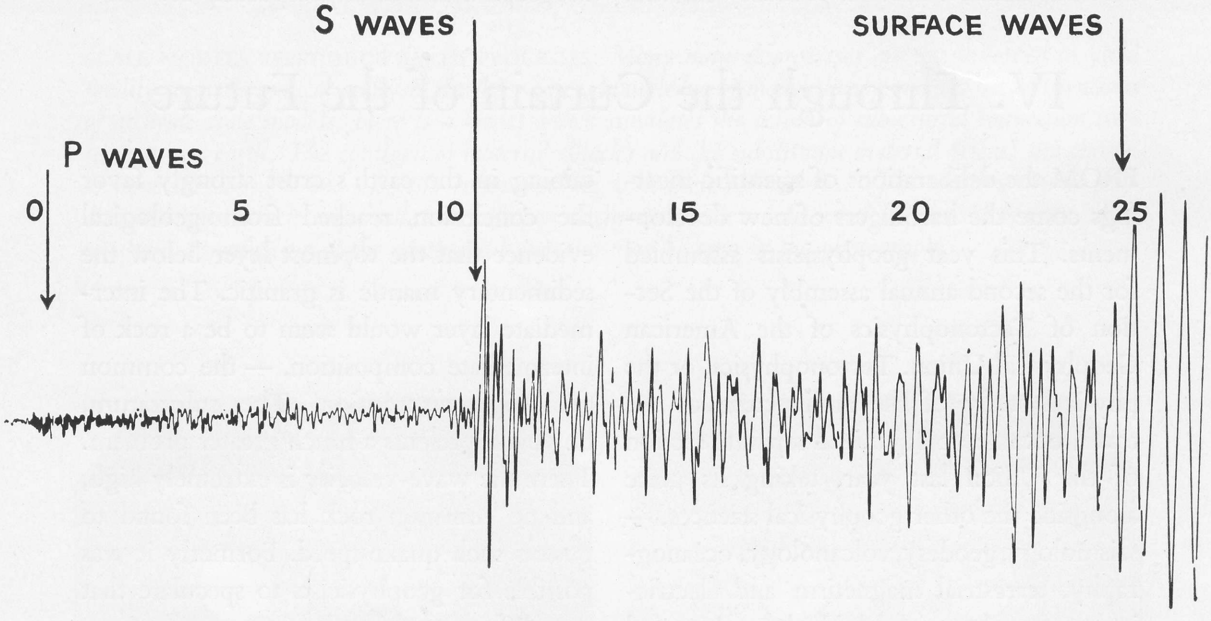
Dr. Birch showed that complete measurements in the laboratory on rocks under all conditions of pressure and temperature obtaining in the earth's crust strongly favor the conclusion reached from geological evidence that the topmost layer below the sedimentary mantle is granitic. The intermediate layer would seem to be a rock of intermediate composition, — the common geological assumption. The substratum, however, presents a much greater problem. There the wave-velocity is extremely high, and no common rock has been found to possess such quake-speed. Formerly it was possible for geophysicists to speculate that the difference was due to temperature, which had not then been duplicated in the laboratory. Dr. Birch has now ruled out this speculation. The only rock which up to date would appear to fit the picture is possibly an eclogite, or a garnet-rich rock.

Dr. Clark reported results of the first measurements on the effect of pressure and moisture on thermal conductivity of rocks. These indicate a small effect of pressure, but a large change due to filling the pores of the rocks with water. With the implied limitations on temperature distribution which these results givė, we move one step further in the approach to understanding of earth heat.

Mr. Griggs and Mr. Balsley reported on new results which extend knowledge of the mechanism of flow in rocks. It has been possible to produce for the first time artificial flow of quartzitic rocks. From "creep" experiments have been derived laws of flow and fracture which have wide application.

Dr. Leet reported on the recent New England earthquakes, which have been so accurately recorded that it is possible to arrive at new conclusions regarding the mechanism of earthquakes. Using the mechanism of rock fracture which has been demonstrated in the Harvard deformation laboratory, he developed a revolutionary new theory of deep-focus earthquakes.

Dr. Harvey Brooks, a Harvard theoretical physicist, has been able to solve the formidable mathematics of periodic convection

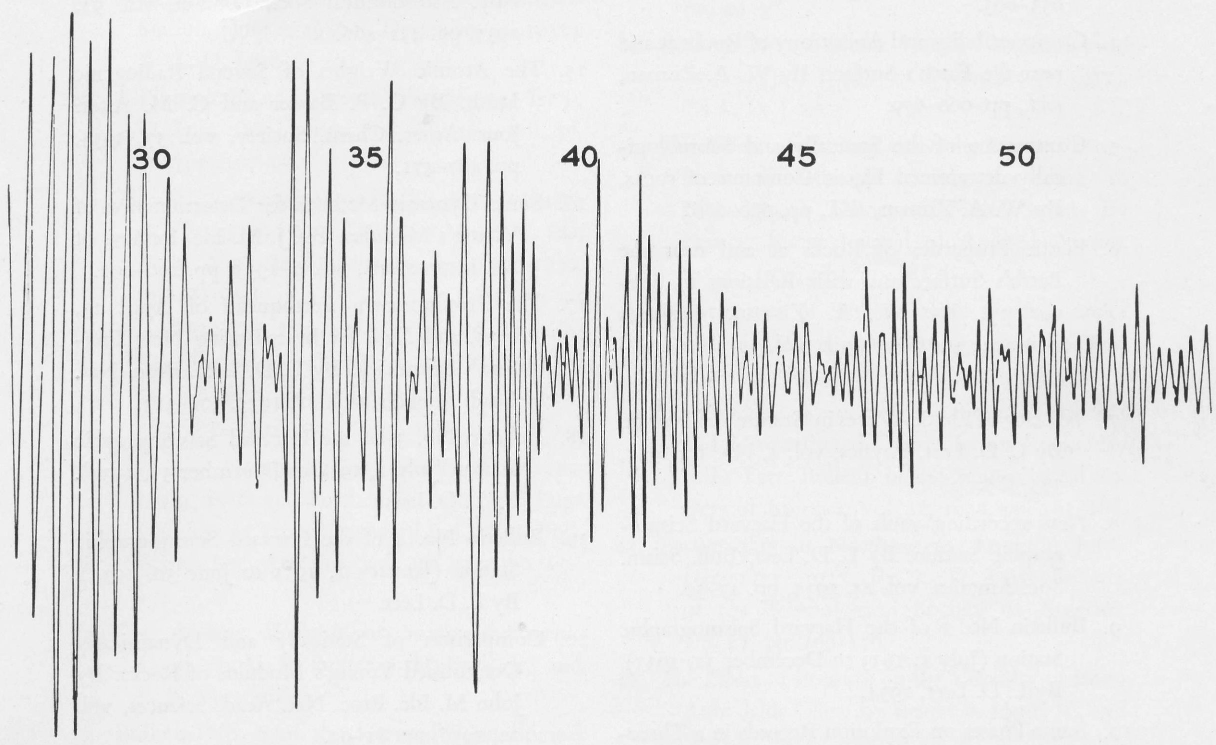


SEISMOGRAM OF EARTHQUAKE AT ERZINCAN, TURKEY, DECEMBER 26, 1939

(Numerals indicate time in minutes)

in the earth. Further, he has been able to compute this effect under the assumption that the rocks of the substratum behave according to laws established in the deformation laboratory. From these involved mathematical formulations he has contributed a great advance in the theory of mountain-building by periodic convection currents in the weak substratum.

Harvard is now pouring out geophysical results in fulfillment of the pioneers' dreams. It represents, however, only a beginning, — more than anything else an indication of the vast potential reservoir of information waiting to be unlocked by the application of the newer physical techniques to geological problems. If we might be vouchsafed a look into the future, it is likely that we should see Geophysics playing the role of midwife as the science of Geology breaks the membranes of uncertainty which bind it to its embryonic position as an observational science, and is born anew to join the exact physical sciences.



APPENDIX I

Publications issued under the Auspices of the Harvard University Committee on Geophysical Research

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2. Instrument for Measuring Poisson's Ratio (an improved apparatus). By W. A. Zisman, Review of Sci. Instruments, vol. 4, No. 6, 1933, 342–344.
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5. Comparison of the Statically and Seismologically determined Elastic Constants of rocks. By W. A. Zisman, *ibid.*, pp. 680–686.
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11. Analysis of New England Microseisms. By L. D. Leet, Gerlands Beitraege zur Geophysik, vol. 42, 1934, pp. 232–245.
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England. By L. D. Leet, Bull. Seism. Soc. of America, vol. 26, 1936, pp. 129–145.

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46. The Effect of Pressure on the Viscosity of Boric Anhydride Glass. By Ernest B. Dane, Jr., and Francis Birch. Journal of Applied Physics, vol. 9, 1938, pp. 669–674.

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PAUL DONALDSON

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Geophysics at Harvard centers around the reproduction of earth pressure and temperature in the laboratory. The cover depicts graphically the successive stages of Professor Bridgman's approach to deep earth conditions of pressure.