EART

by Beno Gutenberg

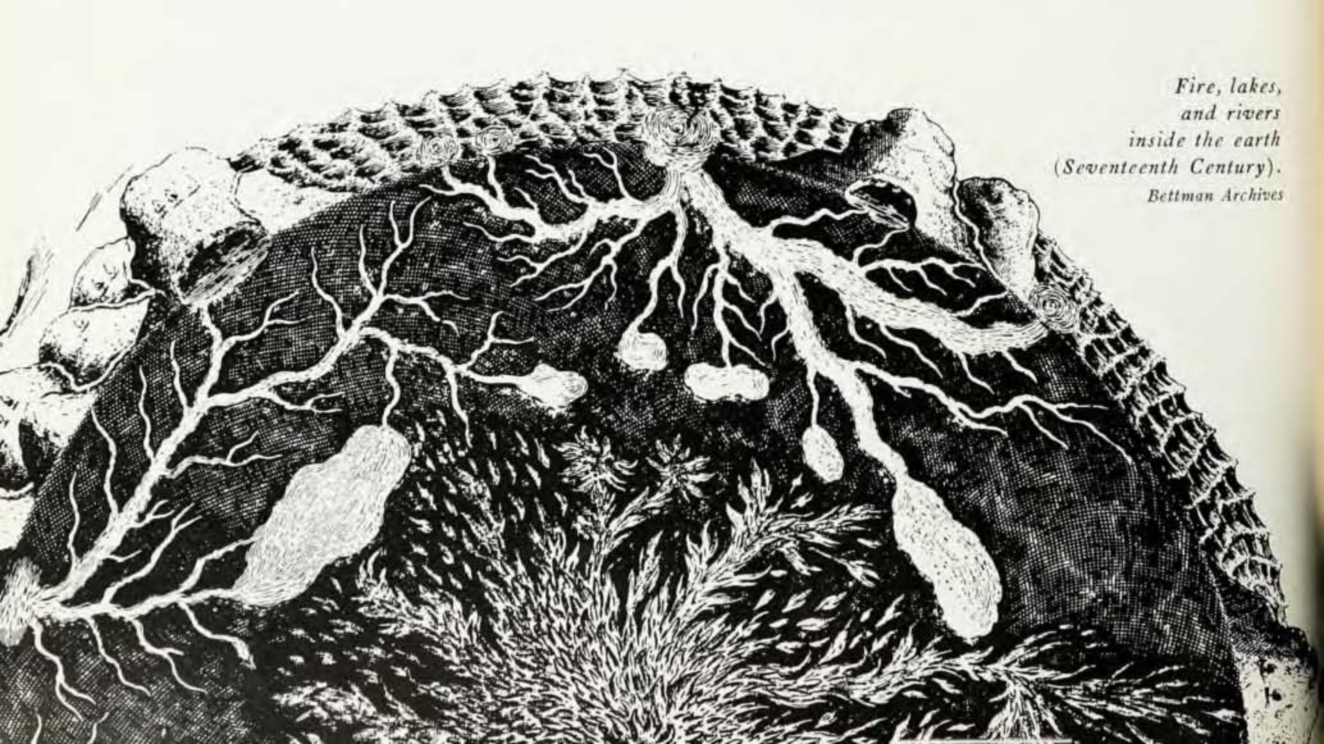
Geophysics is a bridge between sciences which is used less by physicists than it should be, writes a pioneer geophysicist discussing the research problems faced in studying the form, structure, and physics of the earth.

Choosing his equipment and his materials carefully, the physicist most often studies different bits of matter to find the properties they have in common. He works from a diversity of material to a unity of principle that encompasses all the material he studies.

In a sense the geophysicist turns this upside down. He has under his feet a lump of matter—the earth—and he studies the diversity of the physical properties and processes of this globe of material.

Geophysics applies the methods of theoretical and experimental physics to the earth. As a borderline field it is interdependent with a number of sciences, often acting as a bridge from one to the other. Certain of the earth problems have been investigated by the geologist, and the earth's origin has been discussed (though with few definite results) by the astronomers and astrophysicists. Consequently, geophysics has strong bonds with these sciences as well as connections with some others.

The geologists are deeply interested in the results found by the geophysicists and there has developed an increasing cooperation between scientists in these two fields. But strangely enough—and unfortunately—the cooperation between the geophysicists and the physicists is not yet what it should be. In many instances the theory of physical processes fundamental to the investigation of geophysical phenomena had to be developed by geophysicists. For example, geophysicists developed theories concerning the propagation of elastic waves in a medium with discontinuities or with elastic properties changing in



Fire, lakes, and rivers inside the earth (Seventeenth Century).
Bettman Archives

PHYSICS

one direction (they are used in exploring the interior of the earth), and theories concerning surface waves, certain problems of electric and sound waves, and the effects of plasticity in the earth.

Few physicists have been interested in such problems. While geologists usually welcome the presentation of geophysical problems, these problems are outside the usual interest of the physicist. This has led to a puzzling result. Geophysicists, who normally have a background in physics and have frequently had no training or very poor training in geology, join geological societies much more often than they join physical societies.

Three Parts of the Earth

Geophysics covers a very wide ground and no scientist can be familiar with all its aspects, even without considering borderline fields such as geochemistry, bioclimatology (the effect of climate on life), or cosmic phenomena in the atmosphere (which many physicists seem to regard as "pure" physics). This diversity of geophysics is partly due to the fact that the earth has solid, fluid, and gaseous phases, partly to the fact that all fields of physics have their application to one or the other of these parts.

Fortunately, in many instances the fundamental theory is the same or only slightly different for each of the three parts. For example, the tidal forces are the same, although the effects are quite different. In the solid earth, body tides follow the tidal forces almost immediately; in the fluid earth, ocean tides create tidal currents, free vibrations of water bodies, etc.; and in the atmosphere, resonance phenomena are included.

The propagation of sound waves in the ocean and atmosphere follows the same basic equations as the

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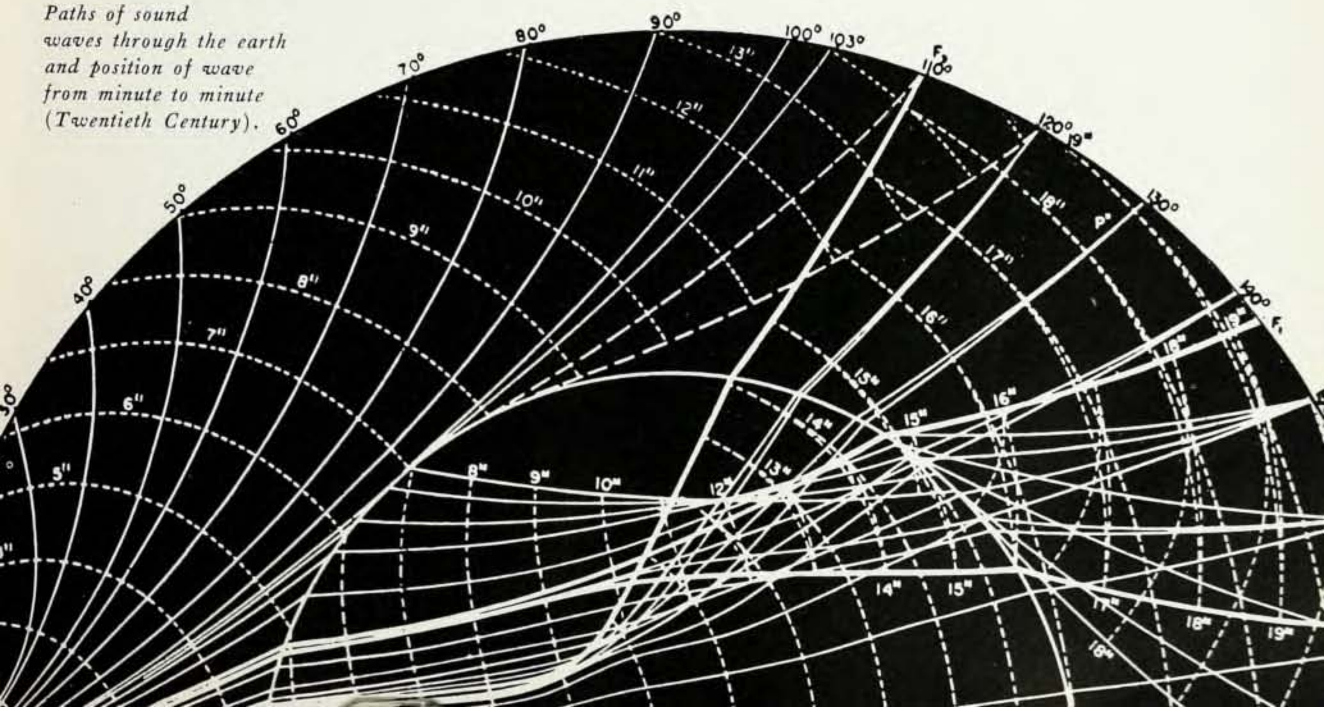
Paths of sound waves through the earth and position of wave from minute to minute (Twentieth Century).



propagation of seismic waves in the interior of the earth; though the latter theory has to include transverse waves. Some methods used in the search for oil (using artificial explosions) and for detection of submarines, are based fundamentally on the same equations. The fact that after an explosion in the air a zone of audibility surrounds the source, followed by a zone of silence a hundred miles wide and then by a ring of abnormal audibility, has its counterparts in the ocean, where there is an even larger ring of silence near the source, but possibly good audibility far away, and in the solid earth, where shadow zones exist for waves through its interior. In all three cases the reason for these zones of silence is the fact that the wave velocity decreases in a limited layer, above the source in the atmosphere, or below the source in the ocean or solid earth. Peculiarly, some basic publications on these physical phenomena can be found in geological periodicals, but few physicists seem to be interested in them.

Form and Structure

A fundamental problem of geophysics, in which astronomers are also interested, is the form and structure of the earth. To a first approximation, the earth is an ellipse of rotation with the shorter axis towards the poles. Yet observations on gravity, as well as geodetic triangulations, indicate that the equator is not a circle, but in better approximation an ellipse with the slightly longer axis pointing near the meridian of Greenwich and the 180th meridian in the Pacific.

The determination of the mean density of the earth is equivalent to the determination of the gravitational constant. Most results have been based on the comparison of the attraction of some small mass, recently a small auxiliary sphere, originally a mountain or a lake, with the attraction of the whole earth. The mean density of the earth is appreciably larger than that of any other planet and no good explanation has been given for this fact.

The change of density with depth can be calculated with fair approximation since the answer must check with the value for the mean density, explain the observed effect on the movement of the moon, agree with the results on discontinuities in the interior of the earth which have been found from the propagation of earthquake waves, account for the observed wobbling of the earth's axis, and give the correct ellipticity of the earth's shape. The density in the center of the earth is approximately four times that near the surface. If the density as a function of depth is known, the pressure can be calculated; the resulting value at the earth's center is several million atmospheres. There is much work to be done on these problems.

The Interior

The temperature in the interior of the earth is not well known; measurements in deep holes show relatively large variations locally. While at the ocean bottom the temperature is everywhere near the freezing point of water, it is several hundred degrees above freezing under the continents at the depth corresponding to the deepest parts of the oceans, and the temperature of lavas at the earth's surface in volcanoes exceeds one thousand degrees Centigrade. Estimates of the temperature near the center of the earth give a few thousand degrees Centigrade. The estimates depend greatly on the assumed rate at which heat is conducted by the material in the earth's core. Determinations of this heat conduction in the laboratory, under high pressures and temperatures, are very scanty. As a matter of fact, determinations of physical constants for rocks under conditions used in geophysics have been made by very few physicists, and geophysicists have done the major part of such research, especially of that done with high pressures and at high temperatures. There is some indication that, at a depth of about seven hundred kilometers, the electric conductivity increases considerably. A similar increase in heat conduction—for in metals both electric and heat conductivity show parallelism—would result in an almost uniform temperature in the deeper parts of the earth.

Heat development in radioactive processes plays an important role in the thermal processes in the earth and the largest fraction of the heat current passing the surface of the earth comes from radioactive processes in the interior. It is still an open question whether the heat radiated into space at the surface of the earth and the heat produced in the interior are about equal or whether the earth is cooling or getting hotter at present, since the amount of radioactive material at various depths in the interior of the earth is roughly known only. The incoming radiation from the sun is important only for the surface climate. Apparently the energy released in earthquakes is an appreciable fraction of the energy radiated into interstellar space.

No decision has been reached thus far as to which parts of the interior of the earth are crystalline and at what depth the temperature is above the melting point of the earth material. No transverse waves (which would provide evidence for solidity) have been observed thus far traversing the core of the earth which has a radius of over one half of the earth's radius. Consequently, it is generally believed that the core of the earth behaves as a fluid. This belief is supported by observations of the rather large body tides and other elastic phenomena. The matter inside the core is usually thought to be iron, but recent theories state that its low rigidity is due to a relatively large percentage of atomic hydrogen.

Laboratory determination of the melting point of rocks leaves little doubt that the temperature existing at a depth of about eighty to one hundred kilometers is close to the melting point and possibly surpasses it. Information from experiments on the change of melting point of rocks with pressure is not sufficient to decide this rather delicate question. The fact that transverse earthquake waves (in addition to the longitudinal waves) pass through the layers at these depths without an unusual loss of energy does not prove that the material there is in a crystalline state because high pressures may prevent relatively fast plastic flow and make transverse waves possible. On the other hand, the wave velocities decrease slightly at a depth of about eighty kilometers and the velocities do not increase noticeably until a depth of about one hundred and fifty kilometers is reached.

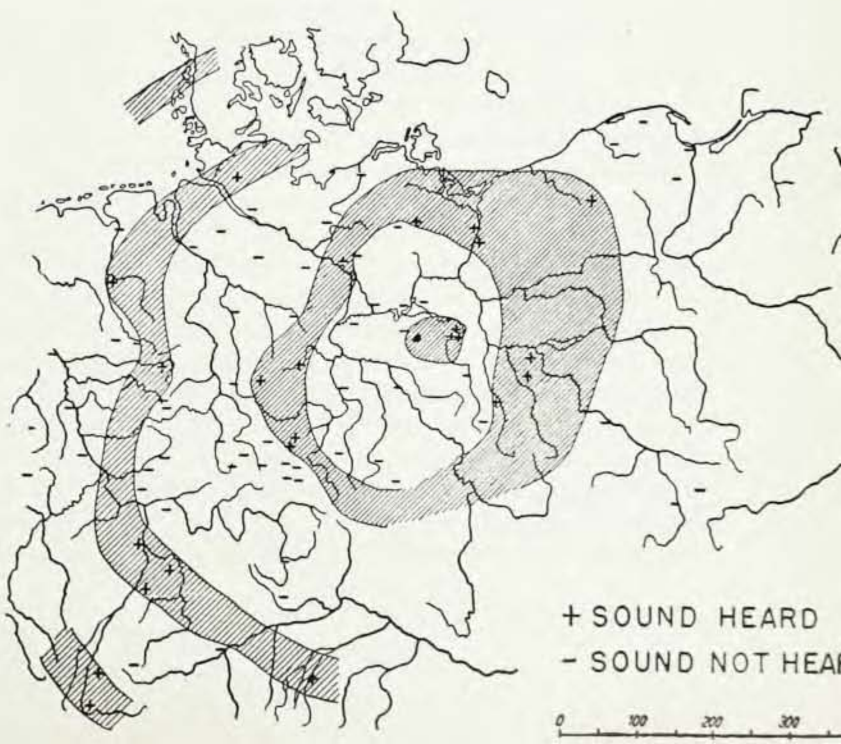
The radius of the core has been determined with high accuracy from waves reflected inside as well as outside. Since these echo waves frequently have a wave-length as short as twenty kilometers, the boundary must be very sharp; the speed of the longitudinal waves drops considerably at the boundary, probably as a consequence of a large decrease in rigidity.

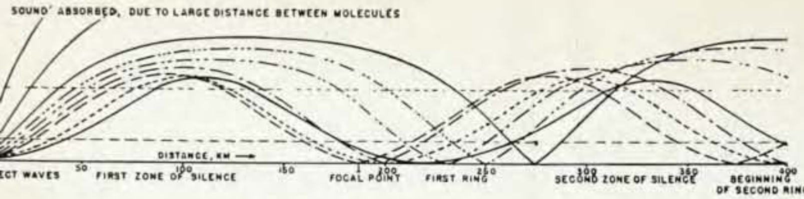
Combining the data on the velocities of the two types of waves and on the density, the bulk modulus and the rigidity inside the earth can be calculated as a function of depth. Furthermore, observations of the tides of the solid earth and of the gyroscopic movement of the earth's poles give information on the rigidity of the earth as a whole. The rigidity increases in general with depth and, near the core, reaches a value about ten times that in the granitic surface layer. It appears to be very small inside the core.

The Crust

Study of the observed uplift of the Scandinavian and Great Lakes regions resulting from the removal of the iceload which had been deposited during the ice age, as well as other phenomena, leaves no doubt

Explosion of buried ammunition showing zones of silence alternating with zones of audibility. From Bull. Am. Meteorolog. Soc., 20: 192, May, 1939.





Paths of sound waves through the atmosphere. Turning this figure upside down gives the path of sound waves through the ocean (with different scales). From Bull. Am. Meteorolog. Soc., 20: 193, May, 1939.

that plastic flow occurs inside the earth at a rate which indicates a high coefficient of viscosity. However, while the outer parts of the earth's crust have a considerable strength (preventing plastic flow under small strain) it is much smaller at a depth of about one hundred kilometers. This is shown, for example, by gravity data which indicate that at that depth most parts of the earth are very nearly in hydrostatic equilibrium (a state which is called "isostasy") and that the masses of mountains protruding as high as ten kilometers above the surface of the earth are compensated below within a layer about sixty to eighty kilometers in thickness. Most of them have "roots" (some of which have been proven by the observations on propagation of seismic waves) which extend deep into the heavier layers below, similar to the behavior of icebergs floating in water.

In certain narrow belts of the earth, gravity deviates considerably from the average value. This is an indication that there are processes operating inside the earth which are large enough to maintain such gravity anomalies. It is certainly no coincidence that negative gravity anomalies, ocean deeps, and earthquakes occurring within the upper thirty to forty kilometers of the earth's crust show a strong correlation within such belts. On the other hand, it has not been explained thus far why there is a similar correlation in space (but not in time) between belts of positive gravity anomalies, of active volcanoes, and of earthquakes at a depth of one hundred to one hundred and fifty kilometers. All these phenomena are strongly developed in structural arcs, surrounding the Pacific Ocean. Inside some of these arcs still deeper earthquakes are found, with depths of as much as seven hundred kilometers, but not deeper. Unfortunately, our knowledge bearing on problems of plastic flow, strength, breaking strength, creep, and internal friction of rock is far from being sufficient for the study of such phenomena.

While seismic waves traveling through the earth give us information about the elastic constants in the interior, the velocity of sound waves through the atmosphere depends almost entirely on the absolute temperature and is not appreciably affected by any other quantity, since the composition of the atmosphere seems to be nearly constant up to at least one hundred kilometers, due to mixture and relatively slow diffusion. Above this level, the rapidly increasing absorption of sound waves makes observation difficult.

Studies of sound waves through the stratosphere have indicated that at elevations near fifty kilometers the temperature must be higher than that at the ground since, at those heights, sound rays are turned back to the surface of the earth. There is good evidence that above an elevation of eighty kilometers the temperature again increases above that near the ground. The temperature maximum which occurs between fifty and sixty kilometers is a result of the absorption of certain solar rays by ozone; the high temperature above eighty kilometers is produced mainly by absorption in nitrogen of other parts of the solar spectrum.

In the ionosphere, the part of the atmosphere above about eighty kilometers, mechanical processes are of decreasing importance; electric processes in rarefied gases are fundamental there. Auroras occur occasionally from one hundred to several hundred kilometers high. Still higher, the atmosphere fades into the interstellar space. There is no boundary between the two, and the limit of the atmosphere is a matter of definition.

The foregoing sketch of a few problems of the earth's physics gives only a vague idea of the whole field, its rather limited connections with geology which have resulted in a strong cooperation of the two sciences, and its strong relationship to physics, which will lead, in the near future, it is hoped, to much stronger cooperation between physics and geophysics than has been true in the past.