SOUND REFLECTIONS in and under OCEANS

Since World War II, when many physicists contributed to the development of underwater acoustics, oceanographers have studied marine animals with sound-scattering techniques and have used seismic reflections to map sedimentary layers deep beneath the ocean floor. The author presented the paper on which this article is based as an invited address at the 8th annual meeting of the Corporate Associates of the American Institute of Physics on September 30.

By J. B. Hersey

Modern oceanography is founded on the curiosity and interest of the naturalist with a bent for things marine who, in pursuing understanding of plants and animals of the oceans, has appreciated the need for comparable understanding of their physical and chemical environment. It is also founded on the interest of the physicist who from time to time has been called in to help provide for a human need: to sound ocean depths for laying cables, to make more reliable fog signals, or to avoid icebergs or deal with submarines. Some of the latter have become interested in the oceans or in the physics of the earth beneath for their own sake. No matter what their individual background, many physicists have found fascination in the science of the ocean.

The interests of naturalist and physicist are in process of being welded together in a common curiosity about the oceans as part of a complex physical and biological system, as a huge natural resource, as a complex device for the conduct of international affairs, for defense, and altogether as one of the largest and most intriguing physical unknowns in the future of mankind.

Physics, both classical and modern, finds a multiplicity of applications at every turn in oceanography from impellors to measure water currents to lasers to measure light scattering in the water. Of these the reflection or scattering of sound has proven to be among the most useful, and its applications are being intensely developed today. In this paper two examples are described: the study of pelagic fishes by means of sound scattering, and the study of sediments of the ocean basins by means of sound reflection.

Sound scattering by marine animals

The importance of sound scattering by fishes and other marine animals was not widely appreciated during the first two decades when echo location by sound was in common use at sea. Following the inventions and developments of Chilowsky and Langevin[1] in France during World War I, echo sounders were rapidly developed during the 1920's and 30's. During this period immense survey programs were completed on the continental shelves of the world, while in the deep ocean many lines of soundings revealed that the relief

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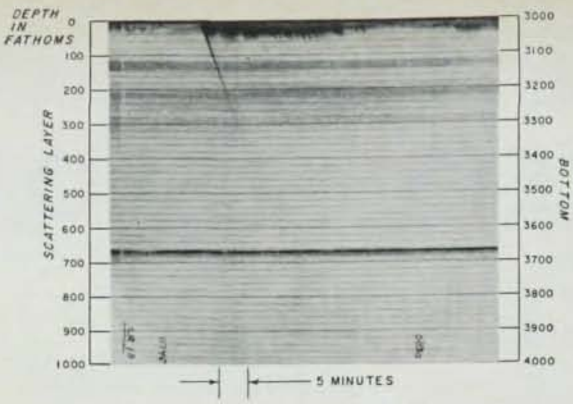

Fig. 1. Echo-sounder record showing three layers of sound scatterers at shallow depths (about 120, 200, and 280 fathoms) in the deep sea. The line of echoes slanting from the surface (left) to about 350 fathoms (right) records the lowering of an instrument from the research vessel.

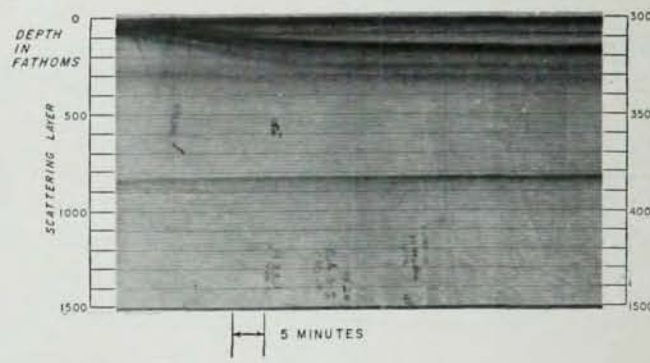

Fig. 2. The sunrise descent of deep scattering layers recorded by a 12-kc/sec echo sounder in the eastern Pacific off northern Chile. The layers migrate downward at dawn as though to hide from the light. A layer which appears to have remained at constant depth throughout the night is shown near 300 fathoms.

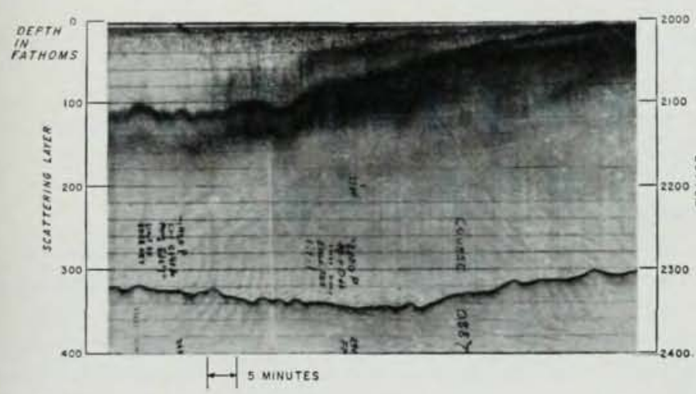

Fig. 3. The sunset ascent of deep scattering layers recorded by a 12-kc/sec echo sounder in the western North Atlantic near 40°30′N, 50°W. The echoes from the sea floor, also shown in Figs. 1, 2, 3 as a continuous echo sequence, lie in a different depth range from the scattering layer. The appropriate depth scale is indicated at right in each case.

of the ocean floor was far greater than had been supposed. There were many shallow places, some of which were obviously the tops of high and rugged submarine mountains.

During World War II, research in support of antisubmarine warfare revealed that there were layers of sound scatterers at shallow depth in the deep oceans whose echoes were observed not only as reverberation on the submarine detectors, but also were easily recorded on ordinary echo sounders (Fig. 1). Frequently the layers had echoes as strong as those from the ocean floor. After some initial confusion about the possibility of electronic artifact, it was strikingly established that the scatterers were animals. This was done at the suggestion of Martin Johnson[2] of the Scripps Institution simply by observing the apparent depth of the layers throughout a day and a night. At dawn the layers were found to migrate downward as though to hide from the light (Fig. 2) while at sunset they returned to the surface (Fig. 3). Gradually, as oceanographers and cartographers accepted the findings and contemplated the significance of these layers, they realized that many of the shoal soundings of the earlier years were simply not from the bottom, but from one of the deep scattering layers. Thus for a time the layers were known as the phantom bottom. They also appeciated that here was a method of great potential value in studying the distribution and habits of animals of the ocean.

If one made reasonable assumptions, it was possible to measure the depth of the various layers, their apparent rates of descent and ascent during diurnal migration, and their geographic distribution. The most difficult problem was identification of the scatterers. The echoes could not be identified with animals for many years despite intensive fish-netting efforts.

Two independent investigations of physical scattering properties provided the first strong clue about identification. At Scripps in the early fifties V. C. Anderson demonstrated that echoes of a

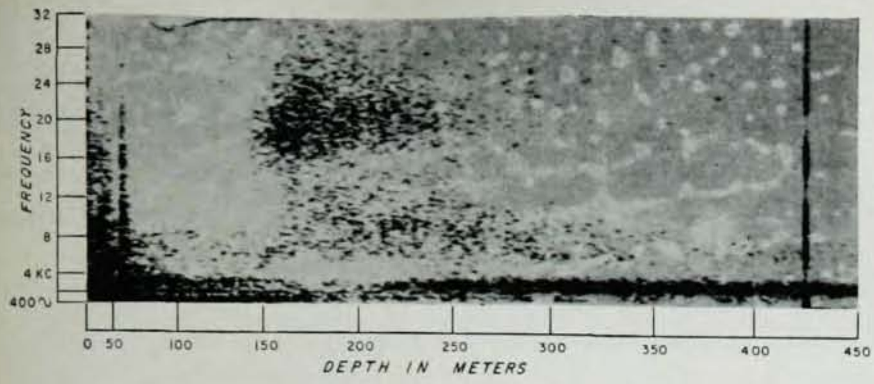

Fig. 4. Sound spectrogram of an observation of deep scattering layers south of Nova Scotia. The sound source is a small explosion, and the receiver has a single sensitive beam directed downward. The source and receiver are close together and near the surface. A magnetic-tape recording was played at quarter speed to a Kay Electric Vibraliser to provide the frequency range indicated. Layers having peak responses near 20 kc/sec, 9 kc/sec, and 3 kc/sec are visible.

broad spectrum pulse from a spark discharged underwater were phase reversed, suggesting that the scatterer was acoustically soft, probably some sort of gas bubble.[3] At about the same time R. H. Backus and I employed small explosive charges to observe the broad-spectrum scattering of the layers south of New England.[4,5] There we found three sets of scatterers, one not found at all by our echo sounders, which resonated at frequencies between 3 and 30 kc/sec (Fig. 4). Furthermore, during migration at sunrise or sunset the peak frequency of the scattering also migrated, to a lower frequency at sunset and the reverse at sunrise (Fig. 5). We surmised that the resonant scattering came from the swim bladders of planktonic fishes, and the most likely candidates at that time seemed to be the myctophids or lantern fishes and certain similar fishes. Circumstantial evidence from fish nettings off California and off New England fitted this picture, but still provided no specific identification of the layers.

Additional physical clues came from studying the frequency migration in detail. We were apparently seeing only the dilatational mode of scattering, the higher modes being well above the frequency range of our equipment. In this mode for spherical or prolate spheroidal bubbles of constant weight, the resonant frequency varies as the 5/6th power of the pressure. We found that in a few instances layers appeared to migrate approximately according to this relationship. However, for more layers the frequency varied nearly as the 1/2 power of the pressure. This relationship is to be expected if the swim bladder remained the same size during migration. It is thus more in accord with the swim-bladder hypothesis since the swim bladder will maintain proper buoyancy during changes in depth only if it stays nearly the same size.[5]

N. B. Marshall[6] has presented extensive anatomical evidence that these small planktonic fishes may be able to secrete and absorb gas during migration, although physiological evidence that they actually do this is still lacking. Thus on all presently known evidence fishes with swim bladders can reasonably account for many of the scattering layers.

During these various researches much has been learned about physical properties, habits, and distribution of these scatterers. The layers are virtually worldwide, but seldom are observed as layers under Arctic conditions. The resonant bubbles vary in diameter from a millimeter or so to a few centimeters, but most of the myctophids, for ex-

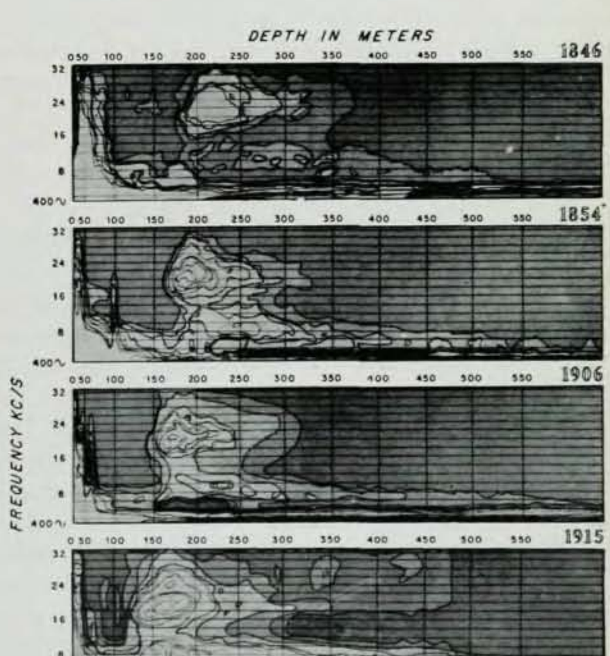

Fig. 5. Contour maps of a sequence of five shots taken during a sunset migration at the times indicated. Contours of equal sound level are two decibels apart with lighter areas denoting highest levels. The third shot in the sequence is the one represented in Fig. 4. Migration in depth and peak scattering frequency is indicated.

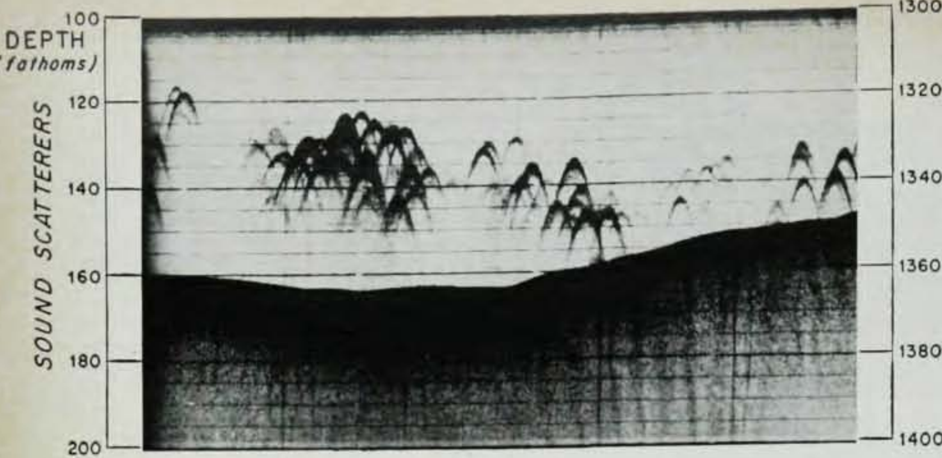

Fig. 6. Sound scatterers over the continental slope east of New England. The species of fish producing the scattering is unknown, and each peak in the record originates from a group of organisms, each such group being regarded as an individual scatterer.
(Courtesy R. H. Backus)

ample, are not large fishes, one 10 cm long being a big one. The population density even in the midst of a dense scattering layer is not necessarily great. In instances when individuals could readily be resolved (Fig. 6) the apparent density is measured as hundreds of cubic meters of water per individual scatterer! In other instances, when no such resolution was possible with similar apparatus, the scattering strength has proven to fit the supposition of assemblages (in the order of 100 per m^3) of smaller animals, possibly the euphausid shrimps.[7] Such a population density of euphausids is regarded as high and probably rare. In the meantime suspended underwater cameras and deep submersibles, both the bathyscaphs "Trieste" and "Archimede" and the soucoupe of Cousteau have been employed extensively in attempts to identify various scattering layers. Even with the aid of direct visual observation at depth the problem remains difficult and subtle. Cousteau has recounted (personal communication) identifying acoustic scattering layers with layers of "snow", the colloquial term for suspended matter (probably organic detritus) frequently observed to form layers in the open ocean. Also the recent observations of "Trieste" by Eric Barham (1963)[8] make a strong case for identifying not only fishes such as myctophids but also siphonophores with scattering layers. Siphonophores are a class of jellyfish many of which contain a gas bubble which must be a resonant sound scatterer. Thus it is apparent that large elements of the once mysterious phantom bottom or deep scattering layer are beginning to be understood by means of a combination of physical and biological researches, each of which supplements and stimulates the other. We do not suppose that myctophids, siphonophores, and euphausids constitute the whole population of sound scatterers; they are merely among the least elusive. In fact other positive identifications have been made, for instance by Johnson et al. (1956).[9] As our techniques, and consequently our understanding improve, we anticipate that acoustic scattering will prove a most powerful tool in observing and measuring the distribution of life in the deep sea.

Sound reflection and ocean sediments

Turning to another borderline field of science, that between physics and geology, the geophysicists interested in the oceans have found since the mid-30's a vast treasure of basic information about the crust of the earth which has had a profound influence on our concepts of the dynamics of the earth. The delineation of the shape of the ocean basins, strictly a product of acoustics, and the discovery that the outer crust of the Earth could be precisely defined in seismic terms by the transition from low *P*-wave velocity to a nearly global 8.0 km/sec below the Mohorovičič discontinuity has ushered in an era in which basic discoveries about the ocean basins are flooding in upon us in bewildering profusion. The seismic refraction method was successfully applied to the measurement of the *P*-wave velocity and the thickness of major units of the oceanic crust of the Earth after its early use in commercial exploration for petroleum on land. This method depends on observing the boundary wave, head wave, or refraction arrival which travel at the seismic velocity of the medium of higher impedance along the boundary between an incident medium of low impedance and a reflecting medium of higher impedance. Although this method quickly provides basic data on the thickness and major structural features of the earth's crust, it tends to ignore the sedimentary blanket of the ocean floor because of its lower velocity and comparative thinness, and it also tends to make exceedingly complex structures appear like uniform layers. In a severe over-simplification the Earth's crust, comprising layers of less than about 6.9 km/sec *P*-wave velocity, is from 30 to 60 km beneath the continents and 4 to 10 km thick beneath the oceans. In the oceans the

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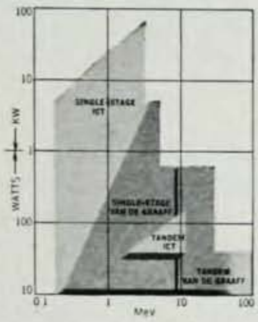

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ICT 500	500	10 mA	5'3"	1.60	4	1.2

The second system utilizes a rigid transmission line to transmit electrical power to the accelerator terminal.

4 MeV ICT	ENERGY (MeV)	CURRENT	DIMENSIONS Length Feet	DIMENSIONS Length Meters
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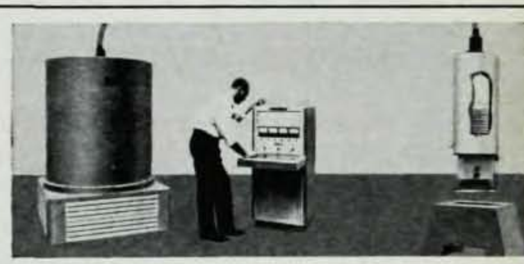

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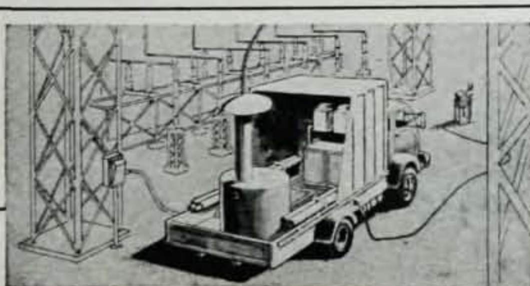

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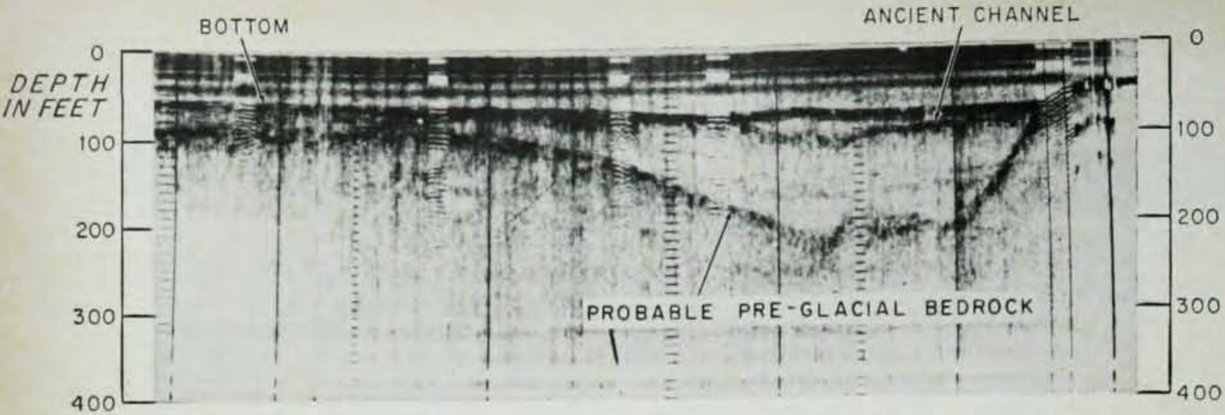

Fig. 7. Seismic reflection profile across buried channel in Narragansett Bay, R.I. This record was obtained using the earliest type of sparker, which stored 8 joules of electrical energy. Outline of the channel, and the two sediment layers which now almost fill it, are clearly visible.

P-wave velocity increases from that of sea water near 1.5 km/sec to that of the deepest crustal layer of about 6.5 to 6.8 km/sec. In regions of unusual structure the crust and upper mantle appear to have blended to produce rocks having velocities in the range 6.9 to 7.6 km/sec. It is obviously of interest to know more of these variations and blends in the deeper high-speed rocks. Nevertheless, it is also of great interest to study the sediments laid down in the modern oceans as a key to the processes of the geologic past. Furthermore, it has long been apparent that the results of the refraction method were mainly valid for broad generalizations about crustal structure and that shallow structures were scarcely explored at all by this method.

Observations of sound reflection, long successful in mapping oil structures on land and in shallow water, were applied to the study of rocks beneath the deep ocean shortly after World War II. The early recordings were made of bottom reflections of explosions detonated near the ocean surface, and it was quickly demonstrated that energy which had penetrated below the sea floor was being received. Weibull, on the Swedish "Albatross" expedition of 1947-1948, shot charges at different depths in the sea and showed that certain pulses of sound, after the first reflection from the bottom, were received at a fixed time after the bottom reflection independent of the depth of the shot or receiving hydrophone.[10] At Woods Hole we showed that the sound spectrum of certain reflections arriving a half second or more after the bottom reflection contained a lesser proportion of high-frequency energy than that of the bottom reflection.[11] Since high frequencies are more highly attenuated in sediment or rock than low frequencies, penetration below the bottom was indicated. Many bottom reflections were recorded, usually spaced several miles apart, during the next two or three years. With few exceptions, however, the wave train following the bottom reflection was so complex and varied so much over a few miles that little geological understanding came from the work and it was dropped.

Development continued since we appreciated that if the information rate could be increased greatly it should be possible to link these dissimilar wave trains through a series of closely spaced reflections that would reveal how one became transformed to the other. This very pattern of change should allow us to deduce much about the structure of the sediments and rock.

It seemed nearly impossible to shoot explosives rapidly enough to provide the necessary data, and the project was delayed for a short time. When in 1950 V. C. Anderson made his sound-scattering experiments with the electric spark,[3] we were reminded that such a source could probably be towed through the ocean while being actuated repeatedly on a regular schedule. The spark had a broad sound spectrum and should behave somewhat like an explosion, though much weaker. We elected to use the recorder from an ordinary echo sounder to control the actuation of a spark-discharge apparatus which we called the sparker. We received bottom echoes of sound pulses from the spark over a hydrophone designed for flat response in the range from 100 to 8000 kcps. The first sparker stored 8 joules of electrical energy, and we were doing well if we converted one percent of it into sound. Nevertheless, with such apparatus we could conduct useful measurements in the shallow waters of harbors and estuaries, like the profile across Narragansett Bay (Fig. 7). This shows a deep channel now nearly filled by two different types of sediment. This weak apparatus was useless farther out at sea, and we quickly developed sparkers storing 500, 1000, 25 000, 100 000 joules. The efficiency of conversion to sound was increased as well, so that by 1961 we were able to make strikingly good, continuous recordings of echoes in water over two miles deep (Fig. 8). But in order to achieve these we had to tow spark electrodes and hydrophones at not more than 3 or 4 knots through the water.

While these developments were going on a comparable system was independently developed in the laboratories of the Socony Mobil Company (the Sonoprobe) and about 1957 other geophysical groups around the country began parallel developments which have proliferated in academic research and in industry. The most powerful and productive model was that developed at the Lamont Geological Observatory of Columbia University which employed small charges of TNT and has been used for several nearly continuous world-circling profiles. In recent years explosives have been abandoned by the Lamont group in favor of a sound source based on releasing a bubble of compressed air suddenly into the sea. Various sound sources; the Boomer, the propane gun, and others have been described and are in use today.[12]

So simple a device for exploration of the ocean has gained rapid acceptance, and, in one form or another, is in use in many countries of the world today.

The development of hydrophones suitable for towing at reasonably high speeds astern of research or survey vessels is receiving great emphasis now. Over the past four years we have learned to tow simple directional arrays of receivers and to tow them rather quietly by reducing flow noise and the effect of the noisy propulsion plants of our ships. This development is expensive and proceeds slowly, but already it has become possible to take good data from reflecting surfaces 3 km or more below the sea floor in the

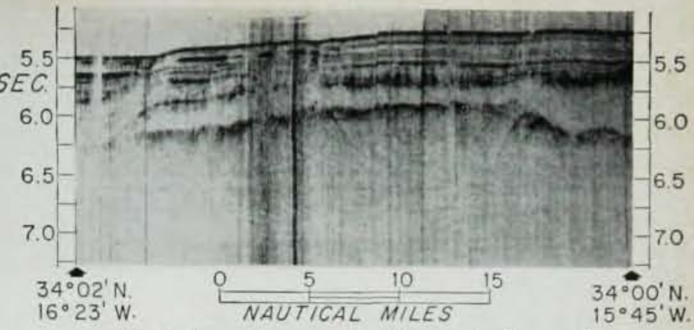

Fig. 8. An east-west profile about 100 miles north of Madeira. This record was obtained using a 5000-joule boomer, towed at speed of 3 knots.

open ocean in more than four miles of water (Fig. 9).[13] Furthermore, this can now be done from a ship proceeding at ten knots or more.

The most reliable information now comes from layered sediments and volcanic flows which form nearly horizontal reflecting surfaces. These lie in or bury a very rough surface which is the upper bound of a rock layer of the crust having a *P*-wave velocity of 5.2 to 5.5 km/sec. It has not been possible to record extensive evidence of structure below this surface by the reflection method. Possibly the very rugged relief will frustrate our efforts to do this, but nevertheless the rewards of success seem easily as great as the fascinating story being told about the sediments of the deep ocean by the seismic profilers of today.

American geophysicists using this technique are developing a general picture of sedimentation in the deep ocean which is the most exciting and diverse in marine science today. The major features of the distribution of modern sediments are becoming known while structures beneath the continental shelves in shallow water and those beneath the deepest ocean basins are revealed with nearly equal ease. The mystery of sediment transport in the deep ocean, where currents were thought to be very slow, is becoming understand-

Fig. 9. Reflection profile taken in more than four miles of water showing reflecting surfaces about 1.5 to 2.0 km below the sea floor. (After Bunce[13].)

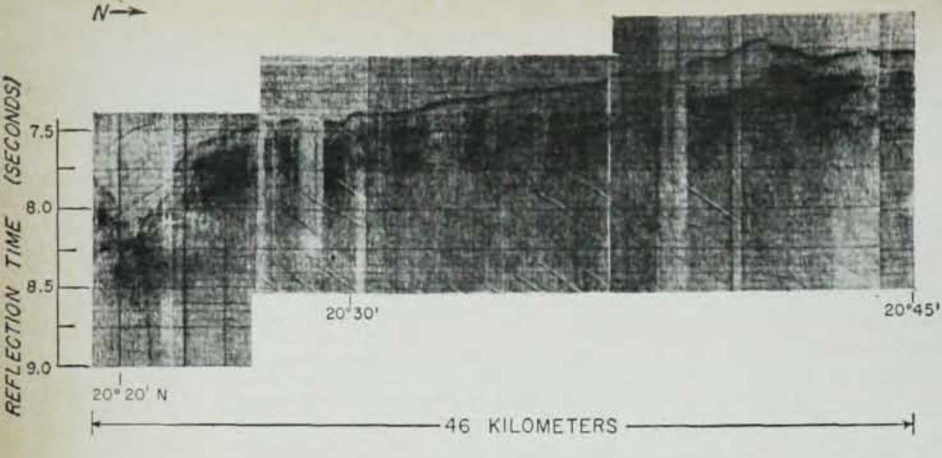

Fig. 10. Reflection profile taken over north wall of the Puerto Rico Trench showing outcrops of sediment layers.

able. But there is one obvious fly in the ointment; we don't know what these layers are, nor can we identify the still deeper rocks even though we know their *P*-wave velocity. Just as in the case of the deep scattering layers we can observe and measure certain very significant properties of the sound reflectors; but their actual identity, which must be known in order to reconstruct geologic history, remains largely hidden. We have had some success at dredging rocks where layers crop out, such as on the north wall of the Puerto Rico Trench (Fig. 10), and we can sample a few meters of sediment by coring. For some years we have been convinced that true identifications and hence trustworthy geological deductions would have to be based on samples obtained by drilling deep into the crust of the earth. A portion of this need is encompassed in project Mohole, which was undertaken by the National Science Foundation to sample the Earth's mantle below the Mohorovičić discontinuity. We have also needed a broadly directed program of drilling to provide sediment and rock samples from many critical parts of the ocean. A recent cooperative approach by several oceanographic institutions and laboratories has started a program of drilling off the east coast of Florida this past spring. This is worth undertaking, largely because we have obtained such beautifully detailed structural profiles to guide the drilling. Through study of the core samples other scientific programs in sedimentology, petrology, paleontology, geochemistry, and other specialties will be able to throw decisive light on many of the great problems of geology such as the age of the modern oceans, the role of continental drifting in earth history, the nature of the interaction between the crust and the mantle. Altogether this particular aspect of the application of physics to submarine geology seems to us one of the most exciting in science today.

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Note: A more complete discussion of research on the deep scattering layers is given in *The Sea*, edited by M. N. Hill (Interscience Publishers, New York, 1962), Vol. 1, chapter 13, pp. 498-539, and a more complete discussion of seismic profiling appears in Vol. 3, chapter 4, pp. 47-72 (1963). Figures 1, 2, and 3 in the present article are from Vol. 1 of *The Sea*; Figs. 7 and 8 are from Vol. 3.