SEISMIC MEASUREMENTS IN OCEAN BASINS[1]

BY

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This paper will include a discussion of seismic effects and measurements in ocean basins as determined from natural earthquakes and from explosions. Earthquake seismology has been related to problems of the oceans since its beginning. In fact, establishment of the international network of seismograph stations, suggested by John Milne in 1897, was due in large part to the correlation of submarine cable breaks with oceanic earthquakes. Much of the great destruction of life and property caused by earthquakes at the borders of oceans results from the great sea waves or tsunamis occasionally generated by them. Recently it has become possible to draw quantitative information about the structure of the sea floor and its underlying rock layers from study of the dispersion of earthquake surface waves along oceanic paths.

On the other hand, explosion seismology began its growth about 1925 with knowledge of the "refracted wave" which had been accumulated in the study of nearby earthquakes; within ten years the first applications of it to problems of geological structure in the open ocean were underway (Ewing, *et al.*, 1937). Through the application of these two techniques, the major features of the geological structure of all oceans are now known.

The objectives of seismic measurements in ocean basins include measurement of the thickness and physical properties of the sedimentary layer, of the layer of silicic crustal rocks, and of the properties of the ultrabasic substratum which forms the upper part of the mantle of the earth. These structural elements of the ocean floor are to be compared with the corresponding ones for continents and for the zone of transition at the continental margins. Data on these structural elements are prerequisites for conclusions about the origin and evolution of continents and other major surface features of the earth, about

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principal mechanisms of deep sea sedimentation, age of the oceans, etc.

Our approach to this problem began 20 years ago with the adaptation of explosion seismology, as developed for oil prospecting, to investigations of the thickness of sedimentary layers in the ocean. Before long the goal of the work was near at hand, for we had not only excellent results at several stations but an excellent technique by which we could rapidly produce additional data on any occasion where two ocean-going ships became available. The physical problem had proved to be less difficult than we had expected, and it was possible to investigate the crust and the mantle in addition to the sedimentary layer.

At that time the possibility of obtaining the services of a team of two ocean-going ships as well as resources for making even a reconnaissance survey of oceans of the world seemed very remote. We believed that, for the immediate future, our seismic measurements would be confined to the area within about 600 miles of Bermuda and that it was of paramount importance to discover some new method by which, with the resources at our disposal, we could learn to what extent the results found by detailed study of the Bermuda area were characteristic of the oceans of the world.

We believed that knowledge of surface waves from earthquakes contributed a relatively neglected source of detailed information about the topmost layers of the earth's crust and that careful study of such data might show that the results from the area around Bermuda were indeed applicable to all oceans. The widespread distribution of epicenters in oceanic and coastal areas together with the extensive files of seismograms from island and coastal stations permit study of surface wave propagation along many great circle paths in every ocean. Thus we undertook a study of one part of earthquake seismology, treating it almost as a branch of underwater sound and attempting to use it as a tool to answer the specific question: Is all oceanic structure the same as that in the western North Atlantic? We now have earthquake data from the North and South Atlantic, the Pacific and the Indian oceans and explosion data from the Atlantic and Pacific, with a little from the Indian Ocean.

Crustal structure for these areas, if we exclude obviously anomalous features such as margins, mountain systems, trenches and island arcs, is as follows. An unconsolidated sedimentary layer, with thickness less than 1 km, covers 5 km of basaltic rock similar to that found near the bottom of the continental crust. The crust is underlain by ultrabasic mantle rock whose properties cannot differ greatly from those found at about 35 km depth beneath the continents.

There are some indications of the occasional presence of a thin layer of consolidated sediments or volcanics beneath the unconsolidated sediments. In contrast, the typical continental crust, composed of a layer about 35 km thick, consists of properties intermediate between those of granite and basalt but tending toward basalt at the bottom. Underneath is the ultrabasic mantle rock, probably dunite or peridotite. These results are compatible with the fundamental geodetic fact that the international gravity formula, established primarily from gravity surveys on continents, expresses the value of gravity at the surface of the oceans almost equally well. The obvious deficit of mass in the water layer must therefore be compensated by an excess of mass in the underlying rocks. It is therefore possible to use the seismically determined layer thickness and demonstrate that the densities required for balance are those of the rock types expected from geological studies.

With the major structural elements of ocean basins now understood, the next step should be the search for small differences between various oceanic provinces, the detailing of critical anomalous areas including continental margins, mountain ranges, island arcs, etc. Before sedimentation in the deep ocean is fully understood, details of layering within the sediments must be mapped. Careful examination of the upper mantle must be made to test whether or not the continents have evolved by differentiation from the subjacent mantle. There are also several puzzling features on oceanic seismograms as well as a number of questions about behavior of surface waves at continental margins which remain to be solved.

Continental margins and anomalous areas usually occur in long narrow belts and include deep sea trenches and submarine mountain chains. Although they are the most significant regions from the standpoint of general tectonic processes in the crust, their structure is almost unknown. The principal methods which can be used for exploration of them are seismic refractions and gravity observations. Seismic studies are usually difficult because of thick sediments, rough topography, and rapid lateral variations of crustal structure. In order to measure properly a section across a continental margin by seismic refractions, it is necessary to orient each individual profile along the strike and to space these profiles at intervals of a few miles along the section. This requires much more time than that which has been available in the past when emphasis was placed on broad reconnaissance coverage. This also requires that the section be situated where a linear structural segment about 60 miles long is available and where some means of precise positioning, particularly for the receiving ship, exists. It is highly probable that explosive charges considerably in excess of 300 lbs. will be required as the profile locations are moved toward the land. Great advantage can be gained by combining gravity and seismic surveys along each section, as has been demonstrated recently by Worzel and Shurbet (1955). The problem of topographic corrections is severe; generally they can be only partially solved at best. The receiving ship must be either anchored or returned periodically to a fixed position, and the sound velocity to be used in allowing for depth changes under both vessels will generally be uncertain. The typical parts of the mid-Atlantic Ridge, for instance, are very rough. It is doubtful if high precision delineation of crustal structure can ever be achieved here.

Increased use of high quality reflection shooting offers great hope in some marginal areas, particularly where the 60-mile segment demanded by the refraction method is unavailable. For example, as a small volcanic island is approached, the behavior of the Mohorovičić discontinuity may be investigated by carrying a reflection profile toward the island from the undisturbed ocean basin, with a tie to good refraction measurements as a starting point.

The great contrast between continental and oceanic crustal thickness establishes the permanence of ocean basins. The thin carpet of sediments, therefore, contains a record extending far into the past. The contribution of both earthquake and explosion seismology has been great in that it has proved that this layer is thin and that at least the greater part of its sediments is unconsolidated. It is now desirable to determine the fine structure within the sediments. By combining high quality reflection studies and refraction measurements in which particular care is taken to record, at close intervals, the various ground wave arrivals for shot distances up to 10 miles, velocity gradients and layering in the sediments have already been found. To obtain even more detailed information it may be necessary to return to the original method of making short refraction profiles with shots and detectors on the sea floor (Ewing, *et al.*, 1946). Even if world-wide correlations of sedimentary layering are found, it may be necessary to wait for the first borehole to interpret these indications of major events in the history of the earth.

It is already clear that there is no great difference in the composition of the upper mantle under oceans and under continents. It is very important to the study of crustal evolution to determine whether or not any systematic difference, however small, is present. An obvious procedure is to make more and better refraction profiles, on continents and in oceans, thereby gradually improving the reliability of the average values. Fortunately, two newly discovered earthquake phases provide a means of comparing continental and oceanic mantle velocities; they are detectable to distances of at least 10,000 km, consist of compressional and shear waves respectively, and propagate in a channel of the upper mantle. These phases, discovered independently by Caloi (1953) and the authors (Press and Ewing, 1955), automatically yield average values, provided suitably located epicenters and seismograph stations are available.

The Sofar channel (Ewing, *et al.*, 1948), discovered during World War II, provides a mechanism for the transmission of sound waves from a small bomb to great distances in the ocean. The position of the bomb can be determined with high accuracy provided three receiving stations are available, leading to many potential applications for position finding in oceanographic research. "Acoustic shadows" and "topographic echoes," both caused by islands or sea mounts which reach near to the surface, have been used as a charting system for certain topographic features. An obvious extension of this work is the use of the T phase (Tolstoy and Ewing, 1950), a Sofar channel wave generated by earthquakes or submarine volcanic explosions. These phases can be of great importance in locating active submarine volcanoes and in some cases they can be of some help in earthquake epicenter location.

The exploration of ocean basins by means of earthquake seismology has been greatly retarded by lack of observations from within the ocean basins. Great dependence has been placed until now on seismograms from coastal stations. At best these records are difficult to interpret because many of the waves to be studied are stopped completely, or scattered, or transformed, or refracted at the continental margin. It is obvious that well equipped island observatories could greatly increase the usefulness of earthquake seismology as a tool for geological investigation of the oceans.

Even with the improvement and simplification in surface wave trains afforded by island observatories, the island itself produces great distortion of the wave pattern when the wavelength is of the order of the dimensions of the island or less. Apparently the best way to overcome this difficulty is to place seismograph stations on the floor of the ocean in areas remote from crustal anomalies.

The material discussed in this paper includes the work of many authors. For references and a more detailed discussion of many of the points, the reader is referred to a symposium on "The Crust of the Earth" (Geological Society of America, 1955).

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