THE STRUCTURE OF THE OCEAN BASINS AS INDICATED BY SEISMOLOGICAL DATA AND EARTHQUAKE EPICENTERS

By B. GUTENBERG

Balch Graduate School of Geological Sciences, California Institute of Technology, Pasadena, Calif., U. S. A.
Contribution No. 226

THE STRUCTURE OF THE OCEAN BASINS AS INDICATED BY SEISMOLOGICAL DATA

When an earthquake occurs, two different kinds of waves are generated: waves which travel through the interior of the earth (space waves), and waves whose energy is propagated chiefly along surfaces (surface waves). The records of both kinds of waves can be used to study certain physical properties of the several layers of the earth, especially of the earth's crust.

According to theory and to observations there are two different types of space waves: longitudinal waves, caused by the propagation of changes in volume (either compression or rarefaction, there being no difference in propagation between these cases), and shear waves (transversal waves), due to the propagation of a shear. The velocities of the longitudinal waves (V) and of the transversal waves (v) are connected with the bulk modulus k, the coefficient of rigidity μ, and the density d of the material in which the wave is propagated, by the following formulae:

$$V^2 = \frac{k + \frac{4}{3}\mu}{d} \qquad v^2 = \frac{\mu}{d}$$

From the seismograms we find the times of arrival of the different phases. Further, in very many cases we are able to calculate the position and depth of the focus, and the time of origin. In such cases we can find the travel time (time between occurrence of the shock and the arrival of a certain phase at the station), and plotting these travel times against the distances, we get the "travel-time curves" which allow us to find the velocities of the several kinds of waves as a function of the depth.

Unfortunately it is very difficult to get travel times of near shocks whose waves run only through the material at the bottom of the ocean. To get true velocities, the instrument must be in contact with the material of the earth's crust beneath the ocean. It is very difficult to state how far this is true in the case of instruments installed on islands. The only observations which may fulfill such conditions to a certain degree, have been published by Angenheister[1] using seismograms near shocks registered at Apia (Samoa). They show that both kinds of forerunners arrive earlier than in other regions considered so far, and they were the first indication of the fact that there are large inequalities in the earth's crust.

Another way to find data on the differences in the earth's crust has been suggested by B. Gutenberg and C. F. Richter.[2] The amplitudes of waves reflected from the surface of the earth depend on the velocities at the point of reflection, in addition to other quantities. The observations show that waves reflected at the bottom in the Pacific basin, with the exception of a few limited areas, and in the Polar basin show usually much smaller amplitudes than waves reflected under otherwise equal conditions in the continents, the Atlantic or Indian Ocean. The maximum difference occurs for epicentral distances of about 5000 km.; at distances of this order Pacific reflections, on an average, have only about $\frac{1}{4}$ of the amplitudes of continental reflections, indicating a higher velocity of waves in the surface layers of the Pacific.

The observations of surface waves, that is waves

[1] Angenheister, G., Beobachtungen an pazifischen Beben. Göttinger Nachrichten, 1921.

[2] B. Gutenberg and C. F. Richter, On Seismic Waves (Second Paper). Gerlands Beitr. zur Geophysik, vol. 45 (1935) pp. 280–360.

which are propagated along the surface of the earth, also can be used to find the velocities of waves in different regions. In a medium which is not homogeneous, the velocity of surface waves depends upon the period. Short waves are propagated only in a thin layer, whereas the energy of long waves is propagated in a thick layer. In general, a considerable amount of the energy of these waves is propagated in that part of the earth's crust with a thickness several times as great as the wave-length. With increasing depth the energy propagated by elastic surface waves diminishes exponentially. If, for example, we have two layers, the upper one with a thickness of ten kilometers and a velocity of three kilometers per second for transversal waves, the lower, with a velocity of four kilometers per second, surface shear waves with a period of one second (wave-length of the order of three kilometers), will be propagated with a velocity of three kilometers per second; if the wave has a period of ten seconds, the wave-length will be greater than the thickness of the layer, so a noticeable part of the energy will be propagated in the deeper layer, and the velocity of the wave will be between three and four kilometers per second. If, finally, we consider a wave with a period of 60 seconds, the wave-length (nearly 240 kilometers) will be large as compared with the thickness of the layer, nearly all the energy will be propagated in the deeper layer and the velocity of this wave will be nearly four kilometers per second. As the whole matter is somewhat complicated, we will not go into detail.

If instead of two layers with constant velocity in each we have a material in which the velocity increases with depth, the effect will be similar; in this case, too, the velocity of the waves will increase with the period. In using this method B. Gutenberg found in 1923 the difference in structure between the Pacific basin and all other regions of the earth.[3]

Combining the most recent data found from the various investigations mentioned so far, Gutenberg and Richter[4] arrived at the following conclusions:

The crust of the earth is divided in most regions into several layers, the uppermost is the layer of sedimentary rocks, with velocities of longitudinal waves from about 1 km./sec. in very unconsolidated recent material to at least 6 km./sec. in very old, consolidated sediments. The thickness of the sedimentary layer varies locally within very wide limits; it may be totally absent, or may extend to depths of over 12 km. (Depths of this order have been found in the Los Angeles Basin by the use of applied seismic methods.) Beneath these sedimentary rocks is a layer which in many cases is known to consist of granitic rock, in which the velocity of longitudinal waves is about 5.5 km./sec. In some regions the sediments are directly underlain by basaltic rock; where data are available, usually one or two deeper layers have been recognized within the crust.

The base of the granitic layer has been found, in the continental regions where it has been studied, at depths between 15 and 20 km. In these same regions the total thickness of the crust (depth of the first major discontinuity) has been found to be from 30 to 50 km. Relatively small values for this thickness have been found for the southwestern United States, western Europe, and northeastern Japan; about average thicknesses occur in central and western North America, and in South America. The largest values found thus far are in the region of the Alps. In the Atlantic and Indian Oceans, the total thickness of the crust is only a fraction of that on the continents; the seismological data offer no evidence as to the nature of the rocks composing the crust in these areas, but in both oceans there still is a well-marked discontinuity between the crustal rocks and the mantle. There is no evident vertical discontinuity between these oceans and the adjacent continents.

In the region of the Pacific basin no marked discontinuity between crust and mantle exists; except for local accumulations of erupted basaltic material, it does not appear that the elastic constants near the rock surface differ significantly from those in the mantle. Data for the north polar basin definitely indicate the existence of a considerable area with properties similar to those of the Pacific basin.

All available evidence indicates that a continental type of structure exists in certain outlying areas of the Pacific Ocean. This is the case in the Polynesian region, including the area west of the Bonin, Marianne, and Caroline Islands. Besides, there is evidence for continental structure in a limited area in the southeastern Pacific, at considerable distance from the coast of South America.

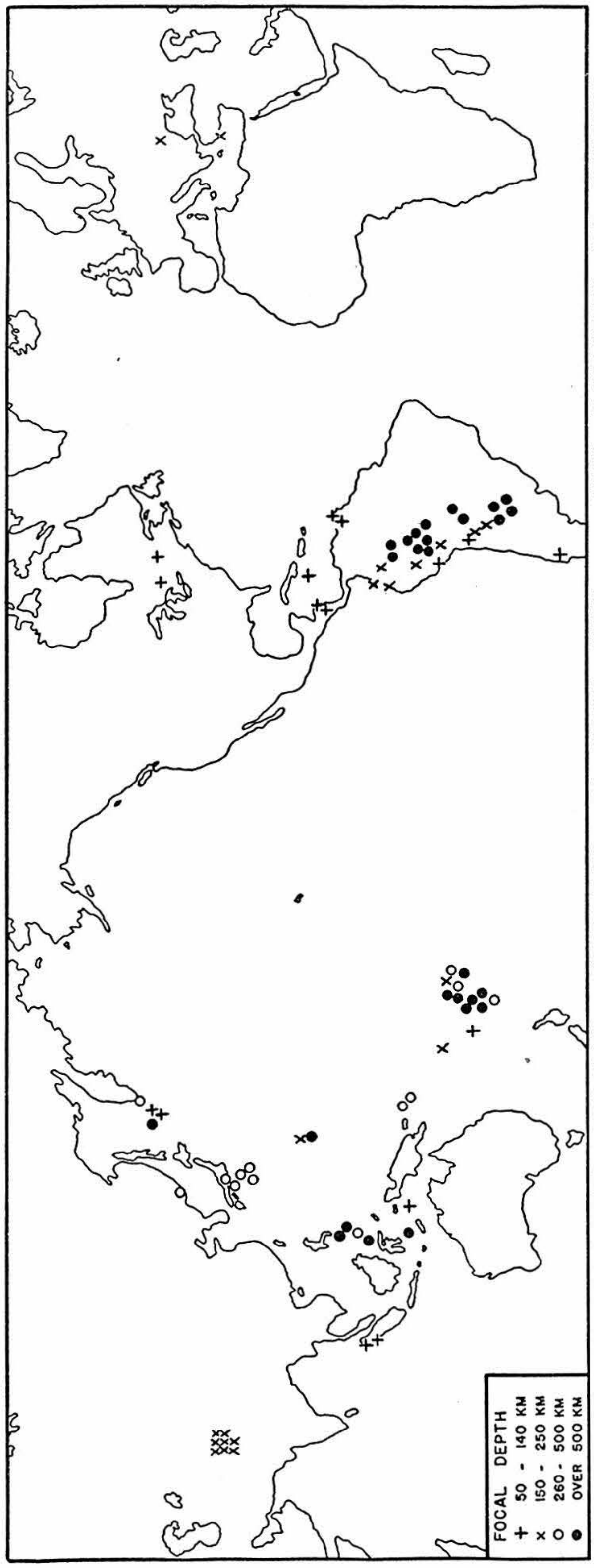
The problem, of what materials the various layers consist has not been solved completely yet. In crystalline rocks, velocities of $4\frac{1}{2}$–6 km./sec. have

[3] B. Gutenberg, Dispersion und Extinction von seismischen Oberflächenwellen und der Aufbau der obersten Erdschichten. Physikal. Zeitschr. vol. 25 (1924) pp. 377–381.

[4] B. Gutenberg and C. F. Richter, On Seismic Waves (Third Paper). Gerlands Beiträge zur Geophysik, vol. 47 (1936) pp. 73–131.

been found for longitudinal waves, in basalt 5–5¾ km./sec. It is very probable that the values found for the upper layer beneath the continental areas correspond to granite under somewhat higher pressure. No waves through more basic rocks have been investigated by means of explosions. It seems to be very probable that the continental layers consist of granite at the top, and rocks with increasing basicity at greater depths, that the bottom of the Atlantic Ocean is formed by the same types of rocks, the layers being noticeably thinner, and that the entire bottom of the Pacific Ocean and all regions of the earth at depths of more than 50 kilometers consist of a very much more basic material than is characteristic of the uppermost part of the continents.

There are other observations confirming these results. Surface waves undergo a certain amount of extinction when propagated. For very long waves, this seems to be the same everywhere. Indeed, the energy of these waves is propagated almost completely at considerable depths, the wave-length being a few hundreds of kilometers, and the structure at that depth apparently is the same in every region of the earth. But if we use short waves we find a very definite dependence of extinction upon the region. The least values are to be found at the bottom of the Atlantic Ocean and on the continents. The values for the bottom of the Pacific Ocean are somewhat scanty, as in this case epicenter and station must be situated in the ocean (Honolulu, Apia). They do not differ much from those just mentioned; however, noticeably larger loss of energy is found for waves which have traversed the boundary of the Pacific Ocean, even if the station is situated very close to the ocean. In particular, the values found from paths along the coast (Japan-Manila, Japan-Batavia) are very high, indicating that it is not a high absorption of the energy at the bottom of the Pacific Ocean that is the cause of the large values there, but the fact of the crossing of the coasts. No corresponding effects have been found from waves passing the coasts of the Atlantic Ocean. In this case, no surfaces between layers of different material must be crossed, but as we found before, and as is stated by the investigation of the extinction of surface waves, the physical coast of the Pacific Ocean (Japan-Philippines-New Guinea) is the boundary, between two completely different kinds of material. The large losses of energy of the surface waves crossing this vertical surface between the material at the bottom of the Pacific Ocean



DISTRIBUTION OF LARGER DEEP-FOCUS EARTHQUAKES IN RECENT YEARS. AFTER B. GUTENBERG AND C.F. RICHTER

Fig. 2

and the very much less basic material in the upper layer of the continents, are caused by reflection and refraction of the energy which arrives there. The vertical extent of these vertical surfaces cannot be more than a few tens of kilometers, as the very long waves seem to show no effect of the kind mentioned.

Nevertheless these vertical discontinuities may affect the conditions down to a few hundreds of kilometers. Investigations on the depths of foci of earthquakes[5] have shown that everywhere in the earth depths of foci of not more than 40–50 km. prevail. In many earthquake regions there are found, in addition, foci at depths down to 100 km. Still greater depths occur in some earthquake regions as in the Hindu Kush (200–250 km.), in the south Atlantic (about 150 km.), Central America (about 130 km.), eastern Mediterranean region (150–200 km.), and many regions surrounding the Pacific Ocean. Earthquakes originating at depths of three hundred km. and more, however, are found only in a relatively narrow belt around the Pacific Ocean. They have been located thus far in Manchuria, Sea of Okhotsk, south of Japan (near 30°N., 140°E.), in the Central East Indies about Celebes, in the Solomon Islands, the Fiji-Kermadec area, and western South America, but not North America. (See figure.) The greatest depths, of between 600–720 km. thus far have been found in almost all these regions, but especially in the Fiji-Kermadec area and in western South America. In general the distances from the Pacific Ocean increases with increasing depth. In South America, for example, the normal shocks are close to the coast, shocks with depths between 100–250 km. are beneath the Andes and a third group of shocks with depths between 600–700 km. have been located east of the Andes. It has been found, besides, that in general the type of movement is the same regardless of depth. That means that if we have a movement towards the north on one side of a fault near the surface, the movement is also in general in a northerly direction on the same side at larger depths. The data available so far are rather scanty in some areas; however, they leave no doubt about the fact that the Pacific Ocean basin bears a unique relation to the occurrence of deep shocks. No similar phenomena have been observed around other ocean basins nor at the bottom of the Pacific Ocean.

If we summarize our results we find that the region comprised within the limits of the Pacific Ocean as given above has one kind of structure and all other regions of the earth, perhaps excluding a part of the Arctic basin, another. In these latter parts of the earth (non-Pacific area) there is a continental layer which consists of several shells. Its thickness is about 40–50 km. under the continents but decreases towards the Atlantic and probably the Indian Ocean, where its thickness is of the order of 20 km. There is no indication that the continents have broken during any geological time and drifted apart; however, our findings would be in agreement with the assumption that in early geological times the thickness of the continental crust was different in many localities from what it is today and that plastic flow in the continental crust may have changed the distribution of land and sea in the area including all continents and the Atlantic and Indian Ocean.

The basin of the Pacific Ocean proper is a unique element of the earth's crust and its boundaries affect the layers down to many hundreds of km. As it is not evident how the continental crust could have been removed in a gradual way from the Pacific Ocean the conclusion seems to be probable that the Pacific Ocean either never has had such a crust or that it has been removed by a cosmic event.

EARTHQUAKE EPICENTERS IN OCEANIC REGIONS AND ALONG CONTINENTAL BORDERS

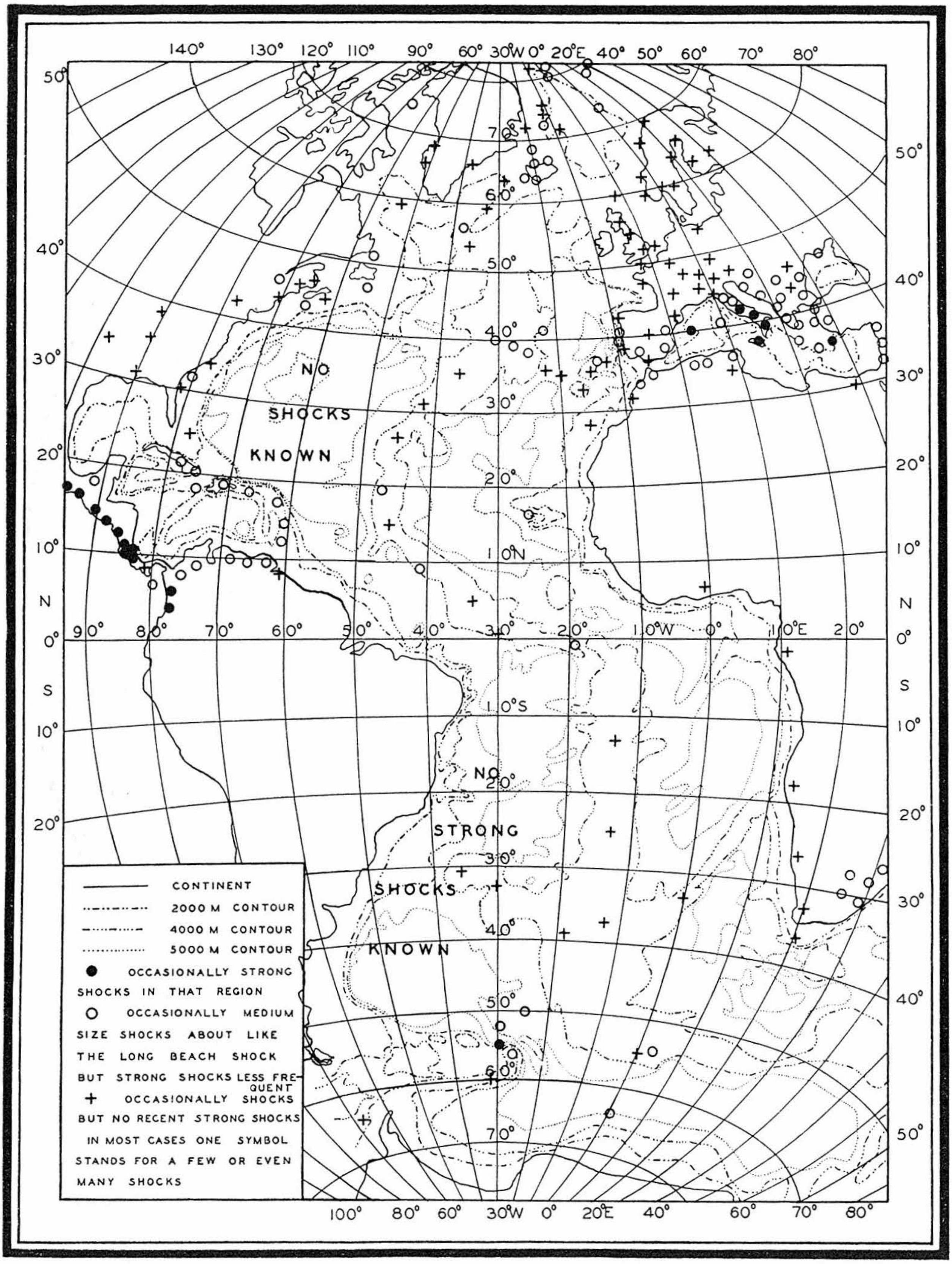
PLATES 24, 25, 26

The accompanying charts are intended to give a general idea about earthquake epicenters rather than to present a map of specific shocks. The following symbols are used:

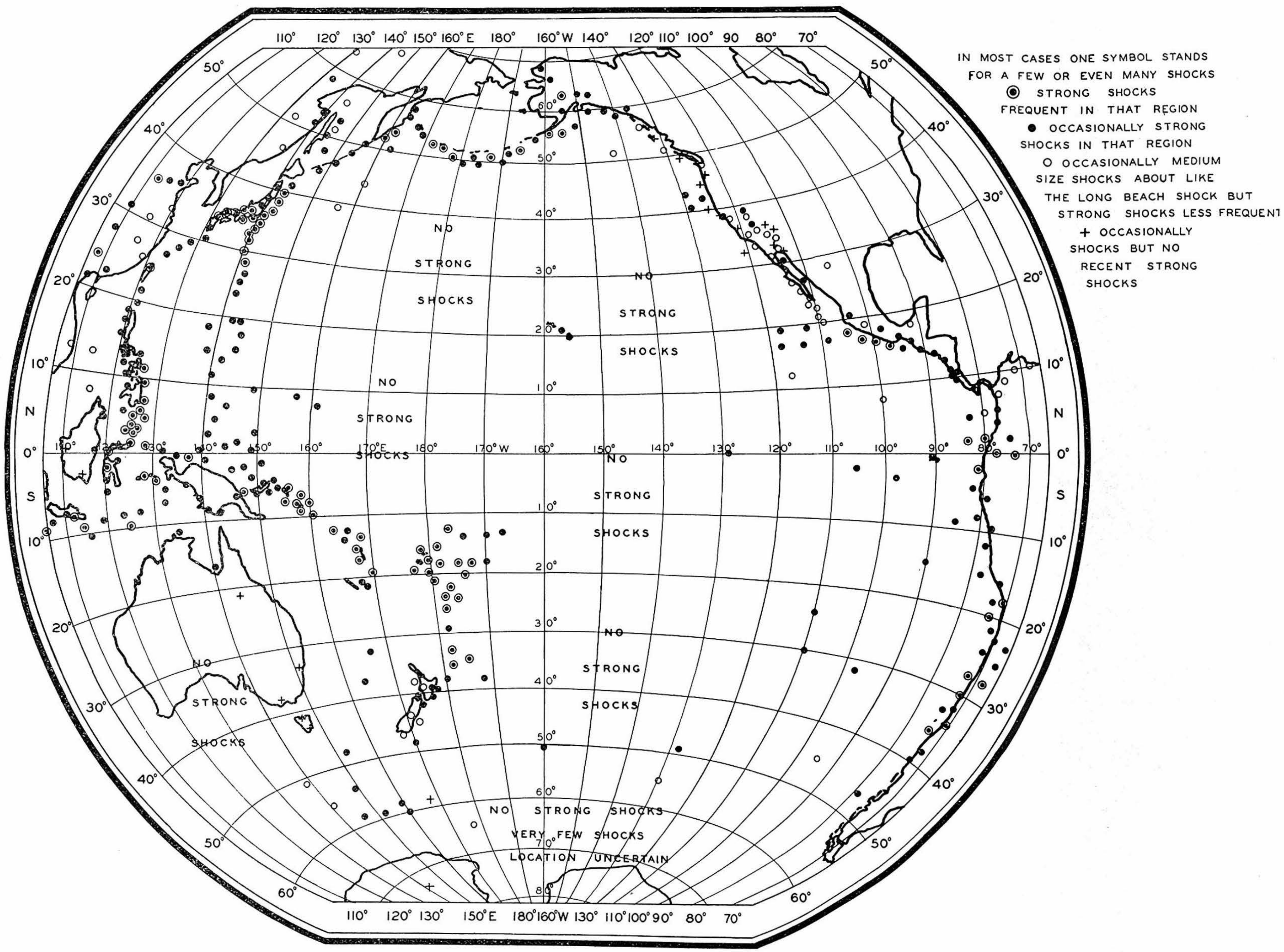
⊙ Strong shocks frequent *in that region*. In most cases one symbol stands for a few or even many shocks!
● Occasionally strong shocks *in that region*.
○ Occasionally medium size shocks (about like the Long Beach shock), but strong shocks rare.
+ Occasional shocks, but no recent strong shocks.

As in many cases the epicenters are not known to a higher degree of accuracy each symbol refers to a region with a radius of a few hundred km. An

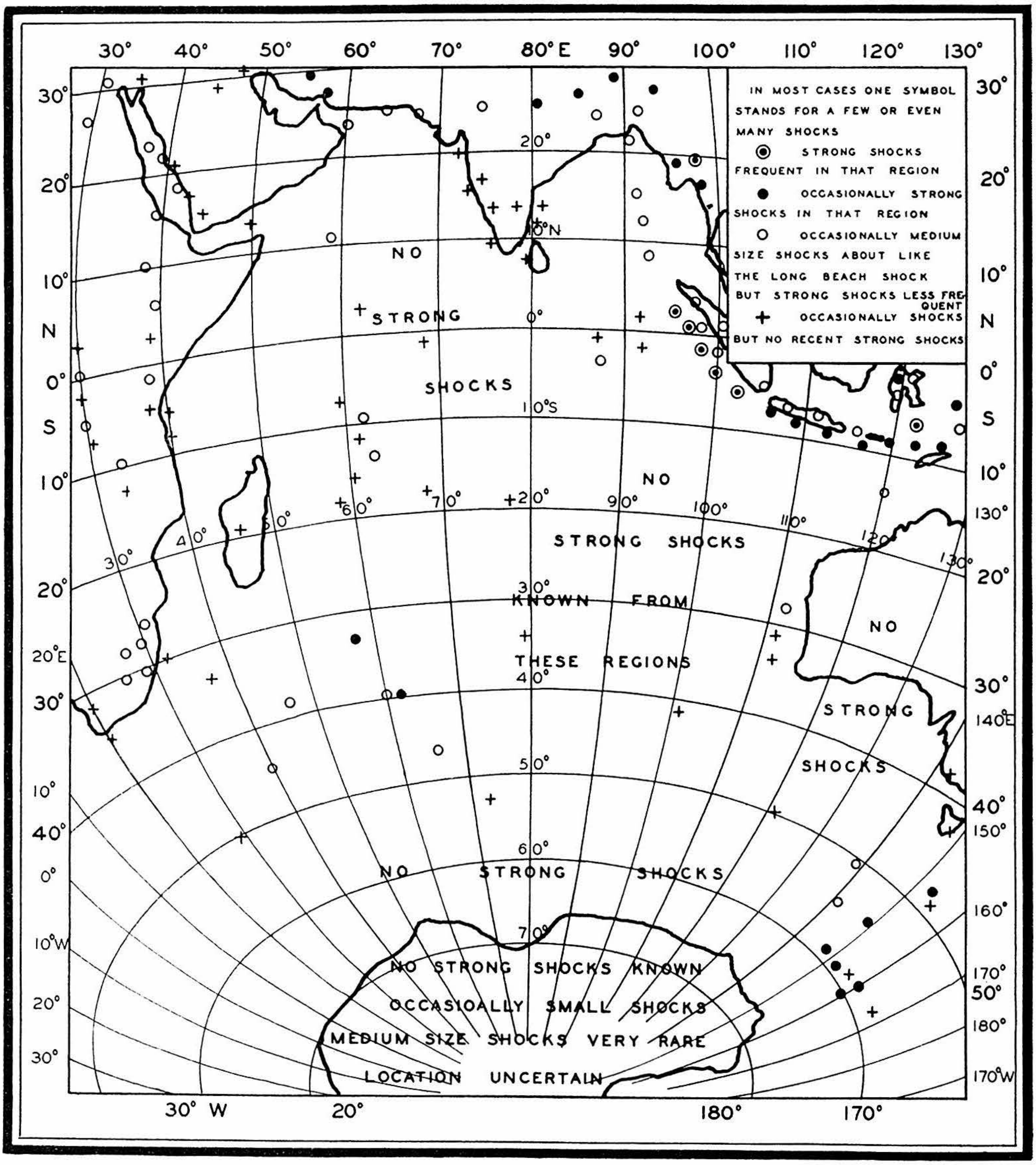
[5] B. Gutenberg and C. F. Richter, Depth and Geographical Distribution of Deep-focus Earthquakes. Paper, presented at a joint session of the Geological Soc. of America, Cordill. Sect, and the Seismological Society of America at Berkeley, April 10, 1937.



Atlantic Ocean, Earthquake Epicenters
(Base chart, after G. Wüst)



Pacific Ocean, Earthquake Epicenters
(Base chart, after A. Defant.)



INDIAN OCEAN, EARTHQUAKE EPICENTERS
(Base chart, after A. Defant.)

endeavor has been made to eliminate the effect of the different density in distribution of the earthquake observatories but it may not have been entirely successful. For example, the Atlantic-Arctic region, on which there have been a few detailed investigations made, may be less active than the map indicates. In the Southern Hemisphere, on the other hand, as there have been only a very few investigations, many earthquakes of moderate size may have escaped attention. But it is my belief that the difference between the bottom of the Pacific Ocean and the surrounding regions is not exaggerated. Our records for recent years have confirmed the indicated relations, the regions with the most epicenters are more distant from us than the quiet regions.

The following is a list of the charts of the different oceans showing the position of earthquake epicenters on the sea floor and on the continental margins:

1. Chart of the Atlantic Ocean.
2. Chart of the Pacific Ocean.
3. Chart of the Indian Ocean.