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Geology of the Pacific Sea Floor

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Introduction

The oceans cover more than two-thirds of the surface of the earth and a knowledge of what lies beneath them is essential to understanding many of the great problems of geology. Are continents and ocean basins permanent? Do the continents move relative to each other? These problems have been recognized from studying the continents where data are complicated by the conflict between the internal forces which elevate the land and erosion which truncates it. Under the ocean, erosion is quantitatively insignificant compared to on land so that mountains retain the shapes given them by internal forces. Consequently submarine topography is nearly equivalent to ideal geological structures on land. Little was known of the relief of the Pacific sea floor before the last decade when oceanographic expeditions put to sea, with sounders capable of reaching any depth. Since then the Scripps Institution of Oceanography and Navy Electronics Laboratory have sounded more than 500,000 km of track (Fig. 1). These soundings and related geophysical observations form the main basis for the present discussion although Russian oceanographers have sounded for comparable distances, and the Swedish *Albatross*, and Danish *Galathea*, and British *Challenger II* expeditions have also made major contributions to knowledge of the Pacific basin.

The topography of the ocean floor has a broad reticulate pattern of elevations and depressions and characteristically the center of each ocean basin is relatively shallow. The elevations and depressions compare in size with small continents or large complexes of mountains such as the complex extending from the Mediterranean to the East Indies. Superimposed on these broad features are deep trenches, linear archipelagoes, and fracture zones, all of which have the dimensions of individual mountain ranges, *e.g.*, the Alps or Himalayas. The relief more subdued than a whole mountain range is only partially known at present. However, it appears that the sea floor is irregular with volcanoes and low hills of undetermined origin except where turbidity currents or very fluid lava flows have buried the hills and formed smooth plains.

The various kinds of topography will be considered starting with the largest. Particular emphasis is placed on seamounts, abyssal plains, fracture zones, and other features which were not known to exist only 15 years ago.

Broad Elevations and Depressions

The greatest topographic feature of the sea floor is an essentially continuous median elevation which extends through the Atlantic, Indian, Antarctic and South Pacific Oceans for a total distance of about 30,000 km[1]. The relief of the elevation above the adjacent basins is 1–3 km and the width in most places is more than 1000 km. This elevation is conspicuously centered in the Atlantic and Indian Oceans where it is called the Mid-Atlantic and Mid-Indian Ridges. In the South Pacific the position relative to the margins of the basin is less obvious but it can be determined by an arbitrary method (Fig. 2). The technique used is to accept the 1000 m isobath as the margin of the ocean basin and to draw a family of lines approximately parallel to and equidistant from the margin by swinging arcs on a globe[2]. The intersections of arcs with equal radii are connected to establish median lines. Consequently any major convexity of the margin of an ocean basin has a median line in addition to the one for the whole basin. The great curve bounded by New Guinea, the Phillipines and Japan is an example of such a convexity in the Pacific.

This method of geometrical construction shows that the crest of the East Pacific Rise lies near the median line between New Zealand and Antarctica but at about 55° S. latitude the crest bends sharply to the east and is about 1000 km east of the median line from the bend to Easter Island. Apparent fault scarps suggest that the bend is an offset caused by faulting or else a discontinuity at the margins of large crustal blocks. A similar bend or discontinuity in the East Pacific Rise near Easter Island occurs where an east-west zone of fracturing intersects the rise.

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[1] M. EWING and B. C. HEEZEN, Geophys. Monogr. *1*, 75 (1956).
[2] H. W. MENARD, Bull. Geol. Soc. Amer. *69*, 1179 (1958).

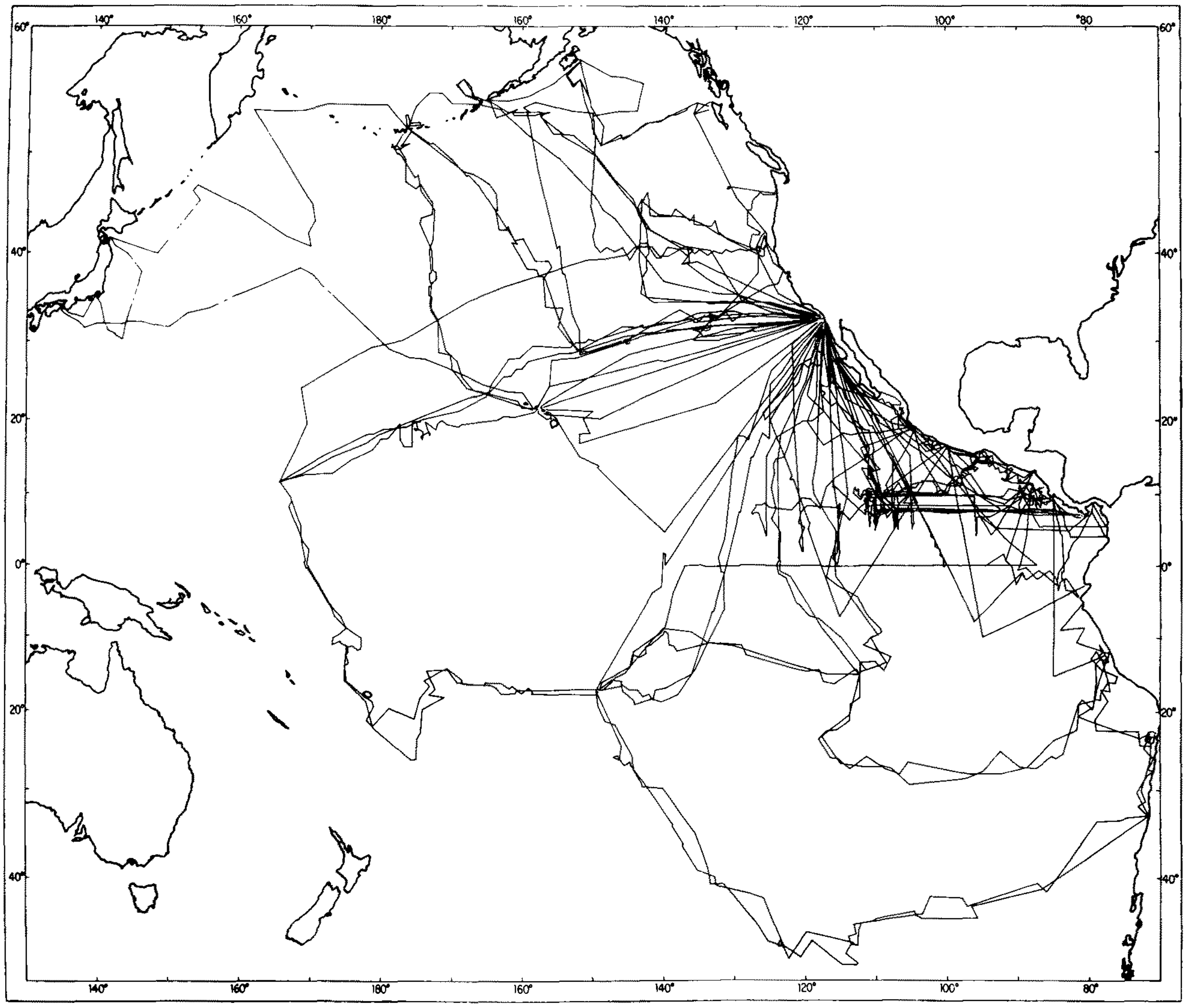

Fig. 1. – Sounding lines of the Scripps Institution of Oceanography and the Navy Electronics Laboratory, 1950–1958. Echograms along these tracks provide most of the evidence discussed.

It is only in the central and North Pacific that an obvious correlation between a geometric median line and a broad median elevation is not found. However, there is a correlation with another type of submarine topography – long, narrow, steep-sided ridges capped with atolls and seamounts. The median line of the whole basin trends northwest from Easter Island through the Tuamotu Islands and the Line Islands to Johnston Island. The Tuamotu Ridge has an area of 200,000 sq km shoaler than 3 km and about 100 atolls and seamounts rise above the ridge. Some of the seamounts are guyots or former islands which are now submerged. The Line Islands rise from the Christmas Island Ridge which also has an extensive area of perhaps 100,000 sq km above 3 km depth and many seamounts and guyots between the islands.

From Johnston Islands the median line has three spurs. The north-eastern spur is not related to any conspicuous topography. The northern spur lies somewhat east of but parallel to the Emperor Seamounts which are a line of large guyots rising from a ridge with about 1 km relief. The western spur corresponds to the Marcus-Necker Rise which, in its eastern half, the Mid-Pacific Mountains[3], has an area of 60,000 sq km shoaler than 3 km. The Mid-Pacific Mountains include about 50 seamounts, mostly guyots, distributed broadly over the ridge. The wholly submerged Mountains and the Tuamotu Archipelago bear a close resemblance in every detail of topography except that the ancient islands of the Mid-Pacific were not capped by reef corals which grew upward as the islands subsided.

The median elevations in most places in the ocean basins are broad gently sloping rises but in the central and North Pacific they are narrow and steep sided. Do these different types of topography represent different stages in development? If they do, the broad rises are an early stage and the narrow ridges are a later one.

[3] E. L. HAMILTON, Geol. Soc. Amer. Mem. 64 (1956).

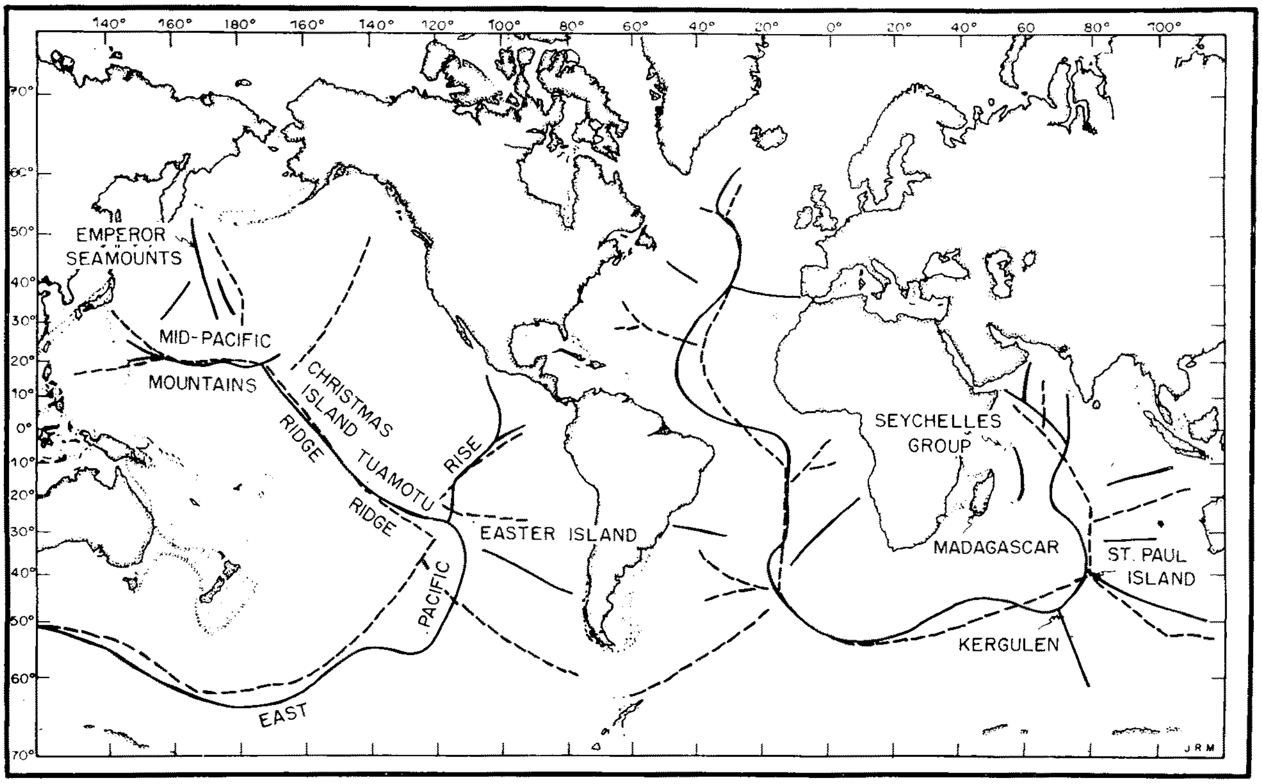

Fig. 2. — Location of the crests of submarine median ridges and rises (solid line) compared with the geometrical median line (dashed) of the ocean basins. Points on the geometrical median line are equidistant from the margins of the continents as indicated by the 1000 isobath which is shown by dotted shading where it does not almost coincide with the shore line and where it is pertinent to the construction.

This is shown by the fact that the broad rises are the locus of a continuous narrow band of earthquakes and active or recently extinct volcanoes. In addition, the heat flow from the earth is highly variable under broad oceanic rises suggesting that very powerful deforming forces are active. The central and North Pacific narrow ridges show no such signs of crustal instability. There are no earthquakes, active volcanoes, or abnormal values of heat flow. On the contrary, deep guyots and atolls bear witness to long-continued quiescence and subsidence.

Abyssal Plains. The floors of many broad oceanic basins are extremely smooth, gently sloping abyssal plains. These plains were discovered about 10 years ago when continuously recording echo sounders became available. Their origin was disputed for several years but, at present, every line of evidence available suggests that they were produced by turbidity currents spreading out on the sea floor from the continents. (1) The plains contain coarse sands and anomalous shallow water fossils which can have been transported only by turbidity currents[4]. (2) The sediment under abyssal plains is several times thicker than is normal in oceanic basins, indicating relatively rapid deposition[5]. (3) Throughout the world abyssal plains occur only where turbidity currents spreading from continents are not barred by bottom topography[6]. Thus they are widespread in the Atlantic but relatively rare in the Pacific because turbidity currents cannot flow past island arcs and trenches. (4) The small scale relief of the plains and their approaches can be explained only by the action of bottom moving turbidity currents[7]. Submarine canyons cut in the continental slope lead out to deep-sea fans which in turn are crossed by channels that extend for some distance on the abyssal plains. In short there are all the elements of a drainage system reaching to a depth of more than 5 km.

An enormous turbidity current apparently swept down from the Grand Banks area off Newfoundland and broke a large number of submarine cables in 1929[8]. Ancient turbidity currents of this scale have been reported as existing in the geological record and they may be relatively common in some places and at some times. However, off central California almost all the deposition by turbidity currents has been in great fans at the mouths of submarine canyons. Turbidity currents rising from slumps on the continental slope between the canyons have played a very minor role in

[4] D. B. ERICSON, M. EWING and B. C. HEEZEN, Bull. Amer. Assoc. Petrol. Geol. *36*, 489 (1952).

[5] C. B. OFFICER, Deep-Sea Research *2*, 253 (1955).

[6] H. W. MENARD, Coll. Internat. Cent. Nat. Res. Scientifique *83* (1958).

[7] H. W. MENARD, Bull. Amer. Assoc. Petrol. Geol. *39*, 236 (1955).

[8] B. C. HEEZEN and M. EWING, Amer. Journ. Sci. *250*, 849 (1952).

shaping the topography. In this region the sediment available to turbidity currents apparently is dumped into the heads of submarine canyons by long-shore drift. Thence the sediment slumps into the canyons and emerges on the fans in turbidity currents.

Features with the Scale of Mountain Ranges

Oceanic Trenches and Island Arcs. Trenches and island arcs were among the first surveyed features of oceanic topography because they were barriers to submarine cables. The island arcs include lines of active volcanoes and they are associated with more large earthquakes and more pronounced gravity anomalies than any other part of the earth's crust. The more or less arcuate trenches which border them are the deepest places in the oceans, which is particularly noteworthy because they are at the edges of ocean basins rather than the middle. At present the greatest depth known is about 10,600 m in the Marianas Trench but very similar depths have been found in the Kurile and Tonga Trenches[9]. Relatively recent investigations of trenches have shown that the shallower trenches in the Caribbean Sea and on the eastern side of the Pacific are partially filled with sediment and, in places, have very flat bottoms. Field seismic methods give equivocal results and it is not yet certain whether the crust under all trenches has been bowed downward to form a root under the trenches. It appears, however, that a small root exists under some Pacific trenches[10]. This point is critical if oceanic trenches are equivalent to geosynclines which are downbowings of the crust representing the earliest stage in the formation of mountain ranges on the continents. Heat flow has been measured along the axes of two trenches and found to be abnormally low. This has been interpreted as suggesting that the downward limb of a convection current exists in the mantle under the trenches[11]. If so, the convection current may be pulling the crust downward to form the trench.

Fracture Zones. Fracture zones are long thin bands that are conspicuously more mountainous than the sea floor in general and which ordinarily separate regions with different depths[12]. The first wholly submarine fracture zones were discovered only a few years ago in the northeastern Pacific Basin. There they are four great bands which are approximately parallel but individually three of them follow great circles (Fig. 3). Each is about 100 km wide and more than 2000 km long. Within the zones are asymmetrical ridges and narrow troughs which are parallel to the general trend. Large volcanic seamounts are also common. The Murray fracture zone may be taken as an example. It extends along the sea floor in an easterly direction from near the Hawaiian Islands to Southern California for about 3000 km. The western section of the zone is composed of two asymmetrical mountain ranges with the steep sides facing and a band of narrow troughs and ridges between. The total relief in a cross section 100 km wide is about 1600 m and most of the changes in depth are abrupt. South of the mountainous ridges and troughs and parallel to them is a great range of submarine volcanoes called the Moonless Mountains because none of them have ever been above sea level although several are more than 3000 m high. In the central section of the Murray fracture zone the northern asymmetrical mountain range disappears and the relief of the southern range becomes greater. In addition a regional change in depth appears such that the sea floor for hundreds of km north of the fracture zone is about 400 m deeper than the sea floor for an equal distance to the south. A single seamount rises above the crest of the range to give a local relief of 4750 m. This seamount, called Erben Guyot, has a flat top from which beach gravels and fossils have been dredged[13]. Although it is now 450 m beneath the sea surface, it apparently was an island sometime more than twenty million years ago. In the section of the Murray fracture zone nearest the continent the relief becomes more subdued but there are several short troughs more than 500 m deep and the regional change in depth still exists. A seaborne magnetic survey of this region shows a north-trending pattern of an malies with magnitudes of about 500 γ[14]. The anomaly pattern is disturbed along the east-trending line of the Murray fracture zone. The pattern can be matched on opposite sides of the disturbance and it appears that it has been offset 150 km which would make it one of the largest fault displacements known. The Transverse Ranges of California lie on the trend of the Murray fracture zone and, at least superficially, they seem to be an extension of the zone.

In addition to the original four, there may be other fracture zones which have not yet been discovered. They are difficult to detect without continuously recording echo sounders and they cannot be confirmed without special surveys. The locations of some suspected fracture zones are shown in Fig. 3. They are suggested by more or less fragmentary evidence from random sounding lines.

Linear Archipelagoes. That the island groups of the Pacific basin lie along straight lines has long been recognized as geologically significant. Modern oceanographic exploration has added little information about the islands except to show that there are similar groups

[9] R. L. FISHER and R. REVELLE, Sci. Amer. *193*, 36 (1955).
[10] R. W. RAITT, R. L. FISHER and R. G. MASON, Geol. Soc. Amer. Spec. Pap. *62*, 237 (1955).
[11] E. C. BULLARD, A. E. MAXWELL and R. REVELLE, Adv. Geophys. *3*, 153 (1956).
[12] H. W. MENARD, Bull. Geol. Soc. Amer. *66*, 1149 (1955).
[13] A. J. CARSOLA and R. S. DIETZ, Amer. Journ. Sci. *250*, 481 (1952).
[14] R. G. MASON, Geophys. Journ. in press.

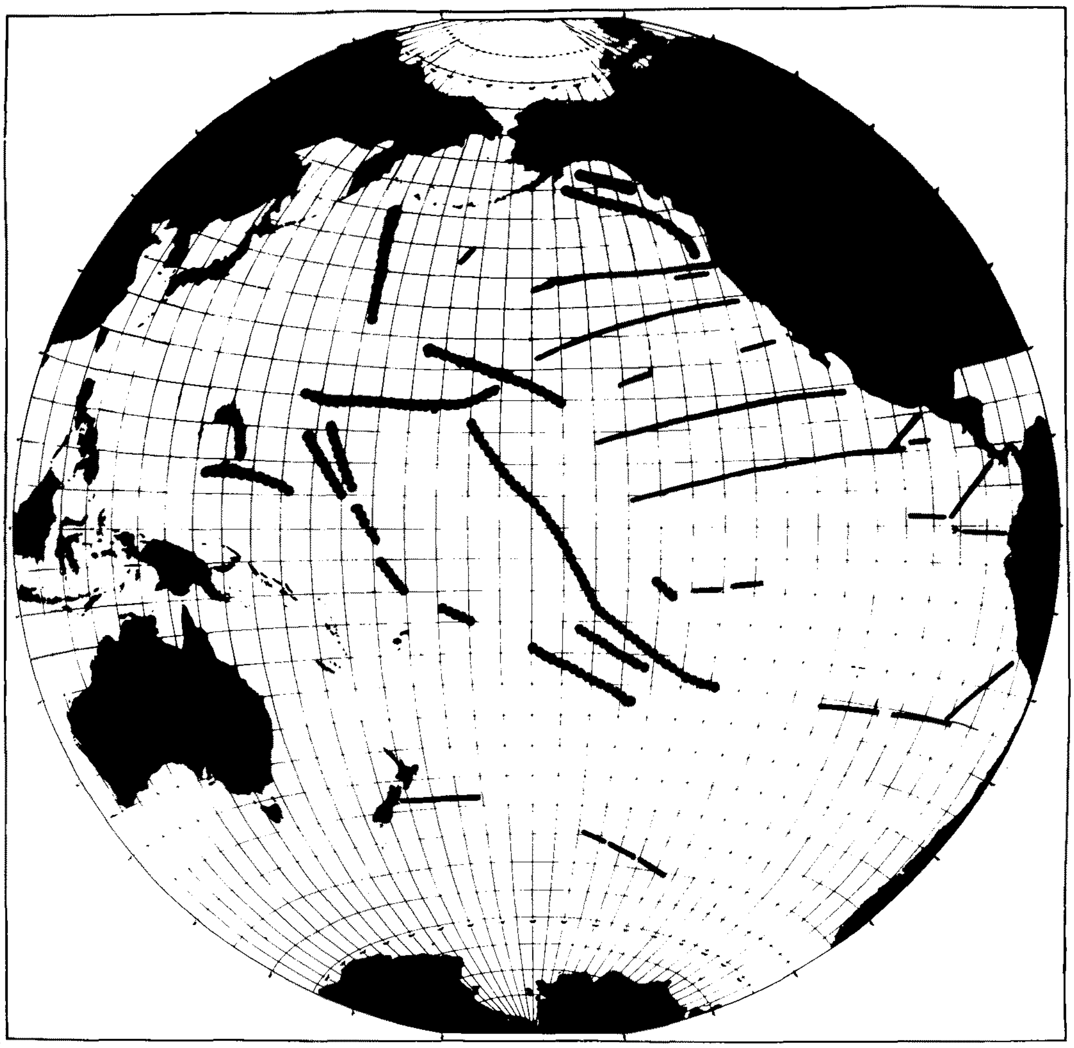

Fig. 3.—Fracture zones and suspected fracture zones of the Pacific Basin (solid lines) compared with linear island archipelagoes including guyots.

of marine volcanoes which are wholly sugmerged and that some of the seamounts formerly were islands. The deep sea floor in the vicinity of island groups has been relatively unknown until recently, however, and it has proved rewarding to study.

Most linear island groups such as the Hawaiian, Marquesas, Samoan, and Society Islands stand above a high ridge which may be caused, in small part, by faulting but appears to be explainable sclely as the result of piling up of lava flows between closely spaced volcanoes. Some linear groups, including the Austral Islands, are relatively isolated volcanoes rising directly from the deep sea floor. The volcanoes of the latter groups are too widely spaced or have not been productive enough to pile up lavas between them and build a ridge.

Although they are linear on a small scale map, the archipelagoes in detail are spread in a band that may be one-fourth as wide as the length if adjacent large seamounts are included with the islands. Consequently they mark a zone of weakness in the crust rather than a single major fault. The center of volcanic activity appears to migrate in a regular manner from one end of some zones of weakness to the other[15]. An outstanding example of the apparent shifting is the Hawaiian Archipelago where the former volcanoes at the northern end are now atolls, the central section is made up of inactive volcanoes, and the southern end has active volcanoes. The Austral Islands and the drowned Mid-Pacific Mountains have had a more complicated history with at least two periods of vulcanism. Sprinkled among the Austral Islands are five guyots at depths of 1100–1500 m. Clearly they are former active volcanoes which were islands but which became inactive and subsided long before the period of vulcanism in which the existing islands were formed.

The enormous load of a group of volcanic islands might be expected to depress the crust of the earth, and a moat, or encircling depression, around the

[15] L. J. CHUBB, Geol. Mag. *94*, 221 (1957).

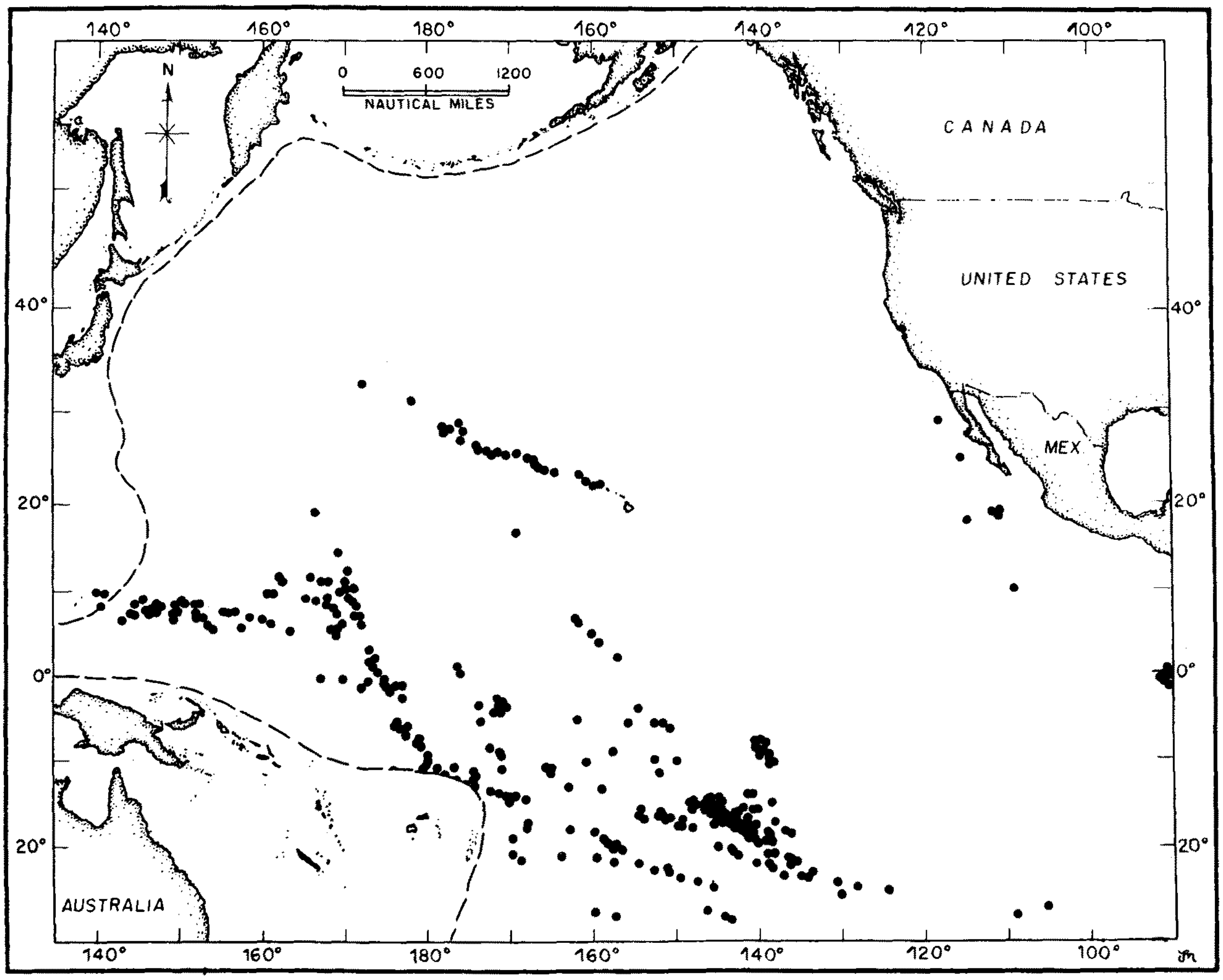

Fig. 4.—Islands including atolls rising from volcanic platforms.

southern Hawaiian Islands has been attributed to this cause[16]. The moat is only slightly deeper than average for the region, but it in turn is encircled by a broad arch which makes the moat more conspicuous. Most archipelagoes are not encircled by moats that are evident in the topography of the sea floor. However, abnormal thicknesses of several kilometers of volcanic rocks lie under the sea floor in the vicinity of many archipelagoes[17]. Inasmuch as the sea floor is not elevated, the upper surface of the crust must be depressed in a moat which has been filled predominantly with lava flows. The fill is called an 'archipelagic apron' and volume considerations suggest that most of the material has flowed from fissures on the deep sea floor[18]. However, some percentage of the fill has spread from the large volcanic islands, both in the form of flows and erosion products. Almost all archipelagic aprons have a very smooth upper surface, which is strikingly different from the normal abyssal hills of the deep sea floor, and this criterion has been used to identify the fill where sub-bottom observations are not available. The smooth surface and extremely gentle slopes indicate that the mode of spreading of erosion products is in turbidity currents. Bermuda Island is surrounded by a very thick apron but the surface is not smooth. In this case a formerly smooth apron may have been deformed into abyssal hills. However, Bermuda Island is a quantitatively trivial source for erosion products and it is possible that the material available has never been sufficient for turbidity currents to produce a smooth apron surface.

A startling recent discovery illustrates how little is known about the relief of the deep sea. The Hawaiian Islands are the focus of a very large number of sounding lines by naval vessels and several reconnaissance studies have been made by research ships with recording echo sounders. Nevertheless a major element of the sea floor topography completely escaped notice until a survey was made with closely spaced sounding lines positioned with precision electronic equipment

[16] R. S. DIETZ and H. W. MENARD, Journ. Geol. *61*, 99 (1953).
[17] T. F. GASKELL, Proc. Royal Soc., Ser. A 222, 356 (1954).
[18] H. W. MENARD, Bull. Amer. Assoc. Petrol. Geol. *40*, 2195 (1956).

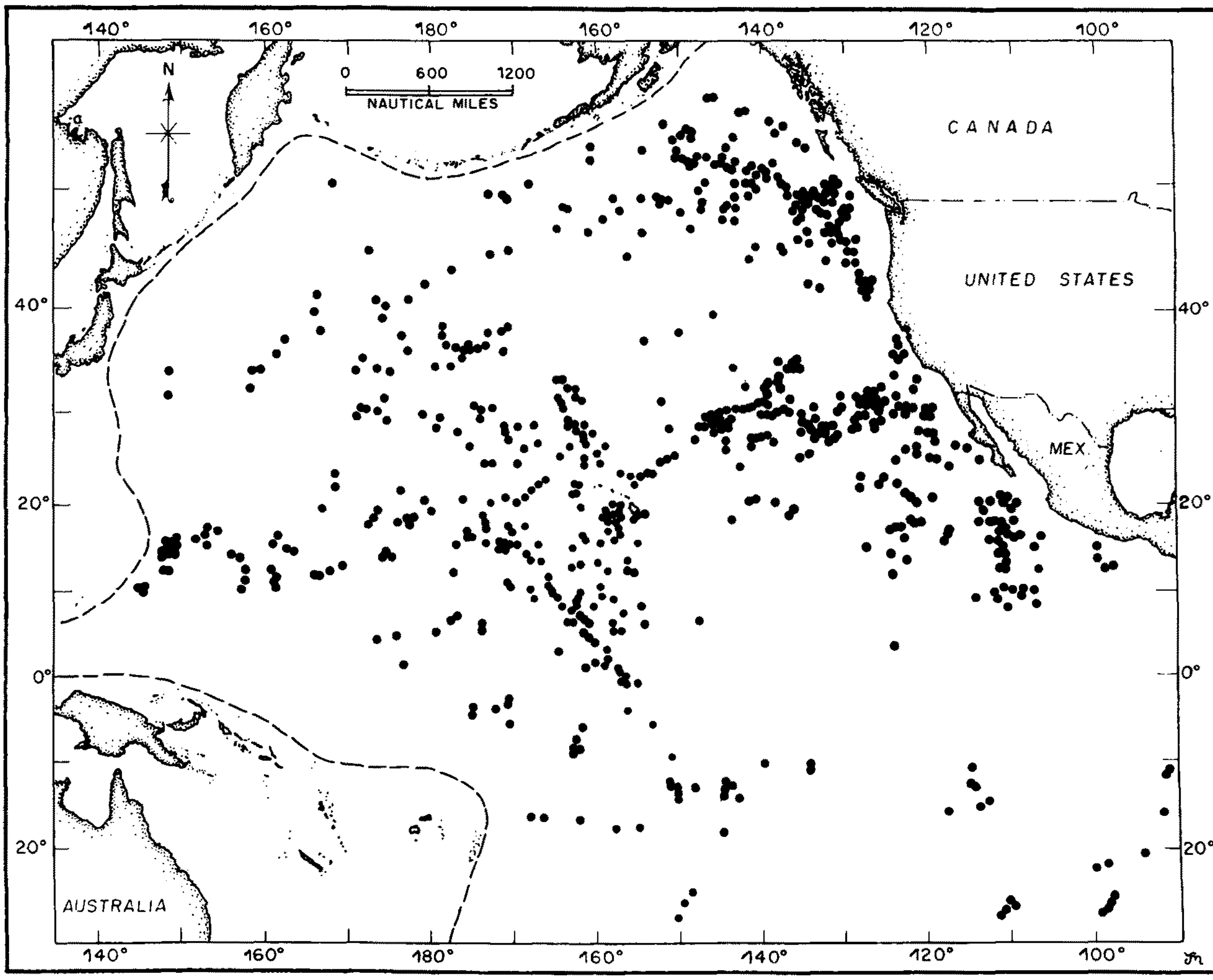

Fig. 5. — Known seamounts other than known guyots with more than 1 km relief. Most seamounts have not yet been discovered. The distribution shown reflects the density of sounding. The dots indicating location are larger than the individual seamounts.

not previously available. Narrow asymmetrical mountains 1–2 km high and 100–200 km long have been found in abundance on the Hawaiian Arch. They form a distinct pattern trending northeasterly on the east side ot the Hawaiian Islands, and southerly on the west side. Similar mountains do not occur on the arch where it curves around the end of the Hawaiian structure.

Seamounts and Abyssal Hills

A seamount differs from an abyssal hill by definition in that the former has more than 1 km of local relief. The dividing line of the two types is arbitrary but two kinds of features may actually exist. Numerous surveys and dredge hauls have established that almost all seamounts are volcanoes and the remainder are fault blocks. Abyssal hills appear to be the same landforms but very few have been surveyed and hardly any have been dredged. Hills have been cored and many have unconsolidated Tertiary sediments at the surface. More recent sediments apparently have migrated off the hills leaving the older sediments exposed. It has been suggested that the migration was caused by uplift of the hills which, judging by their shape, implies doming by laccolithic intrusions. Consequently it is not certain that all abyssal hills and seamounts are features of different sizes but the same origin.

The number of seamounts in the sea is of interest in geotectonics and it can be estimated in the Pacific by several methods with converging results. In the central Pacific Basin as defined by the andesite line there are about 400 islands (Fig. 4) that have volcanoes as a base, and about 1000 known seamounts with a relief of more than 1 km (Fig. 5). By rough approximation, about one-tenth of the area is sounded which implies that nine-tenths of the seamounts are undiscovered. A more quantitative estimate is based on statistical analysis of continuously recorded echo soundings which may be considered as random profiles of the bottom. For ease of analysis it is assumed that the seamounts of all sizes are cones with uniform slopes and that they are randomly distributed. No great error is introduced by the first assumption, but the second limits the size of the region that is studied because some topographic

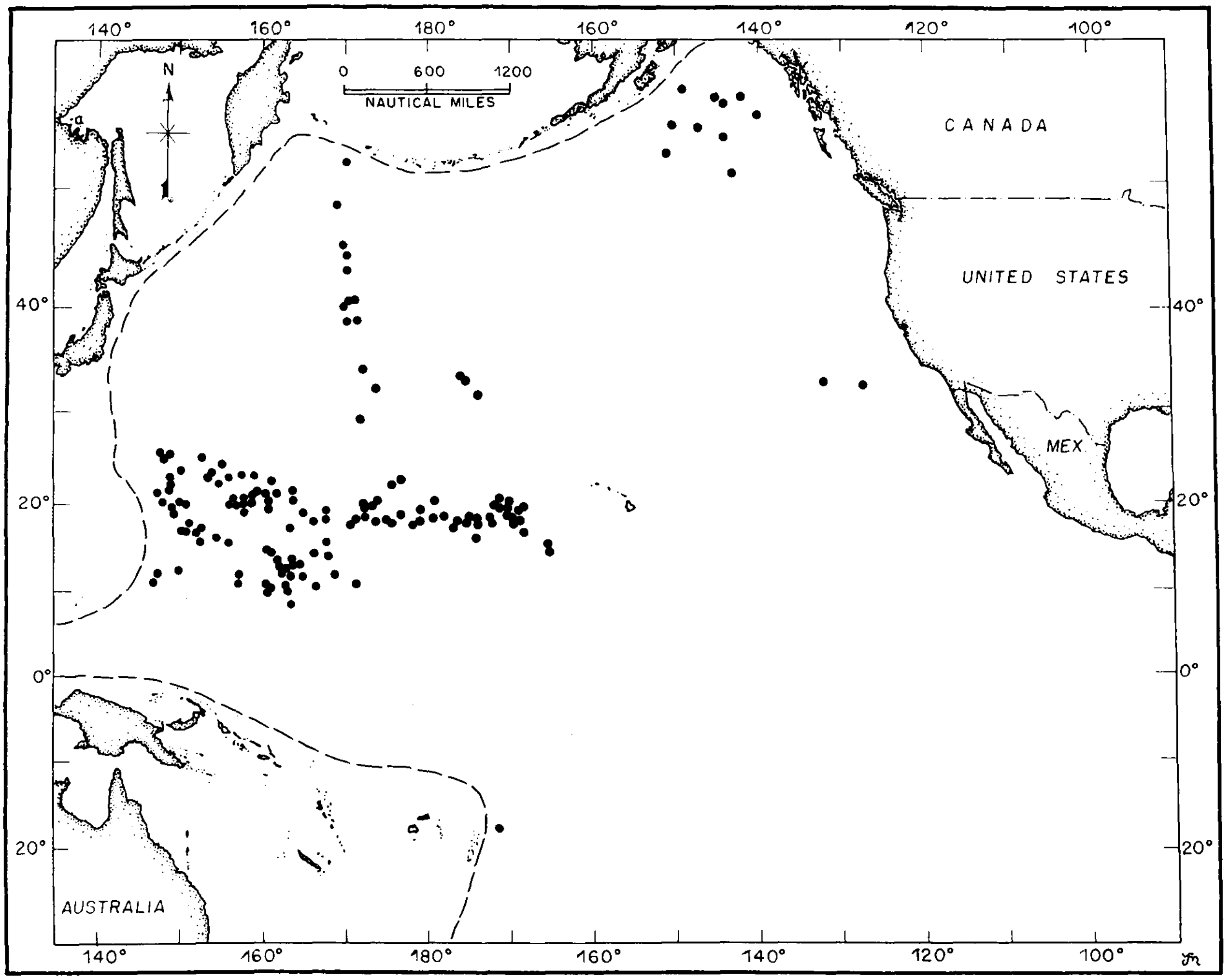

Fig. 6.—Guyots or flat-topped seamounts which were once islands but are now deeply submerged. Compare with the distribution of existing islands (Fig. 4).

provinces have more seamounts than others. The Baja California Seamount Province was selected and the width and height of all elevations higher than 400 m were measured on echograms of 7400 km of track in an area of 1,400,000 km^2. About 10^3 seamounts with at least 1 km relief appear to lie in the area, or about 1 per 1400 km^2. Extrapolating to the whole Pacific Basin and considering various sea floor topographic provinces, the total number would be of the order of 10^4. A third method of estimating is to count the seamounts in the only areas that are sounded densely enough to find every seamount and extrapolate to the remainder of the basin. The same value of 10^4 results.

The distribution of large seamounts and volcanic islands is not uniform; instead they are clustered in groups of ten to a hundred. Abyssal hills are randomly distributed, however, so that all of the sea floor has been the site of vulcanism, intrusions, or faulting. The vulcanism has ranged in geological time at least from the Late Cretaceoüs to the present day and it seems to have been concentrated in different areas at different times. This is indicated by the distribution maps of guyots (Fig. 6) and existing islands. At present, oceanic islands are concentrated in the southwestern Pacific whereas in the past they were also common in the northwestern part.

Tectonic Intensity in the Pacific Basin

The Pacific Basin within the andesite line is generally aseismic and the number of active volcanoes or even of volcanic islands is small. For these reasons it commonly is generalized that the basin has been a stable area in geological time. Modern oceanography has shown that the basin is covered with volcanoes and broken in many places by enormous faults so that it cannot always have been stable. The question raised is whether the present is abnormally quiet tectonically or whether geological time is adequate to produce the volcanoes and faults in a relatively stable basin. The answer depends to a large extent on the time available.

The demonstrable history of the Pacific Basin based on samples is very brief. Cores penetrate only a small distance and could hardly be expected to reach very ancient sediments, even though Tertiary outcrops occur. Dredge hauls of seamounts might sample material of any age because most submarine elevations are swept clean of sediment. To date Cretaceous fossils are the oldest ones sampled[19] but fossils of any kind are rare in dredge hauls and the basalt usually dredged is undatable. The potassium-argon method is capable of dating fresh basalts but the dredge can break off only weathered material unless the dredger has extraordinary luck. If present sampling is considered to be adequate, the Pacific Basin is no older than Cretaceous. However, further sampling may indicate greater age and it seems more logical to assume that the basin is as old as the continents.

As to faulting it can only be concluded that in the past earthquakes have been widespread in the Pacific Basin although not necessarily concentrated in time. The only alternative is to assume that the oceanic type of crust can be faulted without earthquakes and this is not acceptable because large earthquakes occur in a few places with an oceanic crust.

For intensity computations large volcanoes may be considered to lie in clusters of perhaps 20 and the life of a group estimated as of the order of 10^6–10^7 years. For 10^4 volcanic seamounts there are 500 clusters. Granting an age of 3×10^9 years, the rate of formation of clusters averages only $1/6 \times 10^6$ years. Only one cluster need be active at a time and the present vulcanism with four island groups active would be much higher than normal. On the other hand if the time available is only 10^8 years the rate of formation of clusters averages $1/2 \times 10^5$ years. For an average life of 10^7 years, 50 clusters would be active at one time which is far in excess of the present rate. For an average life of 10^6 years the rate would be the same as at present. Within the accuracy of the estimates it appears all the large volcanoes of the Pacific Basin could have been produced since Cretaceous time at the present rate of vulcanism.

Permanence of Ocean Basins and Land Bridges

Recent geophysical evidence reveals that ocean basins are profoundly different from continents. A continent cannot be changed into an ocean basin without changing 35 km of one type of rock into 5 km of another type and lowering the surface by 5 km. The reverse change would be equally difficult but there is no reason to believe that continents cannot be built outward into ocean basins by sedimentation and orogeny.

Nevertheless, the biological evidence for former connections between what are now widely separated continents can be explained without violating geophysical evidence that continents have not subsided within ocean basins. The continents may have moved like ships through the ocean basins, the oceans may have been shallower, or the sea floor may have been elevated and then subsided. Paleomagnetic measurements suggest that some continental drift has occurred but not that the continents around the Pacific Basin have ever been much closer together. Consequently one of the other possibilities seems to be required. Numerous guyots and atolls indicate that island stepping stones may always have been present in the basin. Along a line extending through the Mid-Pacific Mountains, the Line Islands, and the Tuamotu Archipelago the guyots and atolls generally have very little local relief but rather rise from large steep-sided ridges. When the guyots and atoll platforms were at sea level, the tops of the ridges formed three relatively shallow banks each more than 2000 km long. If the banks and islands were contemporaneous, they would have formed a bridge for shallow-water and land organisms that almost spanned the Pacific. There is no direct evidence bearing on the question of contemporaneity and probability in the matter depends somewhat on the process which formed the ancient islands.

The sea floor becomes shallower or is elevated in a sense if a group of volcanoes grows upward and forms islands. It is deepened if the volume and depth of the oceans increase because of the accretion of juvenile water. Vulcanism and accretion of water, therefore, can produce guyots. Alternatively, a section of the oceanic crust may be pushed upward by expansion of the mantle and seamounts may become islands. If the mantle contracts, the islands subside. This alternative mechanism may be the one which has produced the existing broad rises of the ocean basins because in several places the rises have the normal oceanic crustal thickness of about 5 km and the elevation apparently is caused by some process in the mantle. Present day median elevations are extremely long. If the guyot-capped ridges of the central Pacific are the ruins of an ancient median elevation they may well have been contemporaneous.

Zusammenfassung

Als Folge von Faltungen und vulkanischen Vorgängen, die in grossem Maßstabe ablaufen, ist der Meeresboden meistens gebirgig. Lokal dagegen erscheint der Boden flach, da die Berge unter Ebenen sedimentären oder vulkanischen Ursprungs verborgen sind.

[19] E. L. HAMILTON, Geol. Soc. Amer. Mem. *1956*, 64.