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THE OCEANIC CRUST

BY

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In the last half dozen years the nature of the crust under the oceans has been determined by seismic refraction work (Ewing, Worzel, Raitt, Hill, Hersey, Gaskell, and others). The Mohorovičić discontinuity is near 10 km in depth, and above this there are approximately 4 km of rock having the properties of basalt which are overlain by sediments of perhaps ¾ km thickness. These results have been confirmed by surface wave dispersion studies of earthquake wave paths crossing oceanic areas (Wilson, Baykal, Ewing, Press, Jardetzky, Officer, Evernden). All of this is a truly remarkable achievement, for it changes drastically all preceding ideas as to the nature of the crust under oceans. The unexpectedly simple character of this crust lends itself readily to geologic analysis. It may also shed some light on the origin and evolution of the earth's crust as a whole, a subject which has been, until the present, one of almost entirely uncontrolled speculation. We have known from the work of geodesists that the crust of the earth closely approaches isostatic equilibrium. So it is now profitable to make a petrologic balance between the relatively simple oceanic crust and the more complex continental crust. Though perhaps not generally recognized, samples of all of the rock types from the oceanic crust and from the underlying mantle are available, though the authenticity of some could be debated. In terms of geologic structure and history, I propose to discuss rather informally here the consequences which the oceanic crust would require.

The Nature of the Crust. The meaning of the term "crust" has various connotations to various people. In one sense it may connote the rocks above the Mohorovičić discontinuity, thereby referring those rocks below the discontinuity to the mantle. Or it may connote a stronger layer of rock above a more mobile subcrustal zone, the asthenosphere. In this paper I will use the term in the first sense because this gives a definite lithology as well as a definite lower margin as fixed by a marked seismic discontinuity. The other definitions, based on physical behaviour, particularly in the sense of a stronger layer overlying a weaker one, have advantages from the structural point of view, but generally they leave thickness in doubt. In using "crust" in the sense I prefer, it must be borne in mind that a thin crust is not necessarily a weak one or a thick crust a strong one. This would confuse the two types of definitions. A thin crust, in my sense, might act as a structural unit with the upper portion of the mantle and be stronger or weaker than some other sector as the properties of the rocks and physical conditions would dictate.

It has been common practice to subdivide the crust into *sial* and *sima*. These terms refer to generalized compositions, *sial* being those rocks rich in Si and Al and *sima* those rich in Si and Mg. In turn these have been taken to be synonymous with *granitic* and *basaltic*. *Granitic* has been used in such instances in a broad sense, including rock types from diorite to granite, and of course the granitic crust also included various schists, gneisses, greenstones, etc. such as are generally found in old Pre-Cambrian terranes. *Basaltic* has been used in a composition sense rather than as an indication of grain size, texture, or lava flow origin. It might have appeared more consistent with granitic to have called it gabbroic, but historically it was introduced at a time when many accepted Daly's hypothesis of a vitreous basaltic substratum, an hypothesis generally considered to be obsolete today. Peridotitic material below the sima has been referred to as ultrasima by some whereas it may be lumped in the term sima by others. All of the above terms are more or less inextricably associated with one or more hypotheses so that it becomes difficult to use them without suggesting to the reader something more than the layer's composition. Sial, however, retains a certain usefulness and is not unduly involved in extraneous hypothesis.

Before considering the oceanic crust it would be well to outline briefly the status of the continental crust with which it must be in balance. Until recently, seismologists and geologists were strongly predisposed toward giving the continental crust a layered character. Postulates of an upper, intermediate, and lower layer were common in most discussions by seismologists. Today opinion seems to be moving away from this concept, though Gutenberg still favors a two-layered arrangement. At any rate, there is no very marked discontinuity until the Mohorovičić is reached. On geological grounds it seems unlikely that there could be layers representing distinct rock types in the continental crust; rather it is a complex mixture much the same in vertical section as that portrayed in horizontal plan in an area of Archean terrane. It has been repeatedly deformed in the course of time so that much of it should have steeply dipping gneissic structure. The rock types throughout would resemble those of the old Pre-Cambrian as seen at the surface (granitic intrusions, schists, greenstones, etc.) but with an increasing proportion of the more mafic constituents downwards. The latter would be a result of repeated partial fusion in the deeper portions and of intrusion of the resulting liquids into the higher portions. The concentration of the more refractory constituents downwards and of less refractory upwards would result in bulk properties such that seismic velocities would increase with depth. In general, the more refractory groups of minerals give the higher seismic velocities.

The continental crust as envisioned above would be heterogeneous on a small scale (50 km) but homogeneous on a larger scale (1000 km). The Mohorovičić discontinuity is a uniquely sharp boundary seismologically but it could be irregular on a small scale.

The transition from continental crust with its base near 35 km to oceanic crust less than one fourth as thick takes place in a horizontal distance of perhaps 100 km. This would mean that the Mohorovičić has a slope of perhaps 15° downward from sea toward land. While the exact nature of the transition is not known, the recent work by Worzel on the gravity data and by others of the Lamont and Woods Hole groups on the seismic data should clarify the situation for the Atlantic coast of North America in the near future.

The average depth of the oceans is 3.8 km, but this is a rather meaningless figure for present purposes, since it averages the depths over the continental slope, deep sea floor and various ridges and seamounts. What is significant to the present discussion is the depth of the deep sea floor where it is uncomplicated by the above mentioned features. Over much of the oceans, great stretches of fairly level floor are found near 3000 fathoms, or approximately 5½ km. On the floor are unconsolidated oceanic sediments of variable thickness, but 0.7 km would be a good average figure (see Brilliant and Ewing, 1954, and Ewing and Press, 1952). Below is a layer generally considered to be basaltic in composition for which an average thickness of 4 km will be accepted here. This lies on the Mohorovičić discontinuity roughly 10 km below sea level. Below the discontinuity, rocks of peridotitic composition are found. Gaskell (1954) has summarized the velocities and layer thicknesses from seismic refraction work up to 1953, and a number of more recent profiles may be found in Ewing, Sutton and Officer (1954).

Evidence of the Character of Rocks in the Oceanic Column. The unconsolidated sediments found on the ocean floor have been described from many cores and dredgings, so no further consideration will be given to them here. Skipping for the moment a consideration of what lies between the sediments and the Mohorovičić, let us consider the rocks below the discontinuity, because these are also known with a fairly high degree of certainty. These rocks are peridotites, consisting approximately of 4 parts magnesian olivine, 1 part enstatite, 1 part chrome disopide and 1 or 2% picotite. Ross, *et al.* (1954) have described more than a dozen rocks of this type which have been brought to the surface as foreign blocks in basaltic volcanoes. All samples have the same four mineral phases, and Ross, *et al.* have shown that chemically the minerals are practically identical from all of the localities studied. Their samples come from three continents and from oceanic islands. There can be little question that the samples do represent the material from beneath the Mohorovičić, and it is interesting to note that *the composition is the same below the oceans and below the continents.*

Table I gives the bulk chemical analysis of one of these peridotite xenoliths from an extinct volcano near Ludlow, California and of the peridotite from St. Paul's Rock in the Atlantic Ocean off Brazil (see Tilley, 1947). Note that the two analyses are practically identical. St. Paul's Rock represents an actual outcrop of the material

TABLE I. Analysis of Peridotites from below the Mohorovičić

	St. Paul's Rock Peridotite (a)	*Ludlow California "Olivine Nodule"* (b)
SiO_2	43.97	44.35
Al_2O_3	2.89	2.97
Fe_2O_3	1.04	.67
FeO	6.89	7.59
MgO	41.11	40.80
CaO	2.35	2.55
Na_2O	.07	.20
K_2O	Nil	.01
H_2O+	.35	.06
H_2O-	.20	.03
TiO_2	.17	.14
P_2O_3	ND	.02
CO_2	ND	Nil
Cr_2O_3	.50	.41
MnO	.13	.13
NiO	.21	.31
CoO	trace	ND
CuO	Nil	ND
NaCl	.09	ND
	99.97	100.24

(a) Analyst H. G. C. Vincent (see Tilley, 1947).
(b) Analyst R. B. Ellestad, new analysis.

which has world-wide occurrence as xenoliths in basalt. The same four mineral phases are present in it. The only difference is that the enstatite has exsolution lamellae of diopside parallel to {100} whereas the enstatite in the xenoliths does not. This merely indicates that the St. Paul's Rock sample cooled slowly, permitting exsolution, whereas the peridotite xenoliths, which came rapidly from a hot environment at great depth where the temperature was too high for exsolution to occur, were quenched upon reaching the surface. St. Paul's Rock appears to be the western end of a great fault scarp paralleling the equator and extending eastward through the Romanche Trench (Fig. 1). This may be a fault zone similar to those described by Menard (1954) in the eastern Pacific. Duplaix and Cailleux (1952) have found small fragments of peridotitic material in the samples dredged from the floor of Romanche Trench. It appears that this fault has enough displacement to bring sub-Mohorovičić material to the surface at St. Paul's Rock.

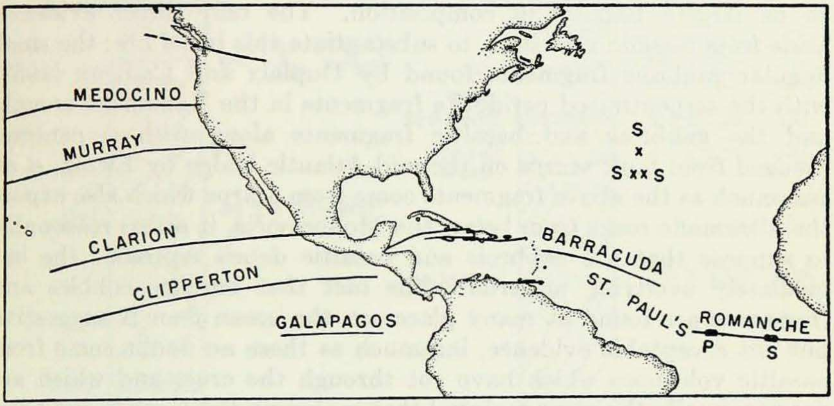

Figure 1. Great fault zones on the ocean floor. Four large zones in Pacific, after Menard (1954). The Barracuda and St. Paul's-Romanche zones in the Atlantic are added by the writer, and Eardley (1954) suggested the Pacific Galapagos zone. A seaward extension of the Montana Lineament is also postulated. P = peridotite; S = serpentinized peridotite; localities are mentioned in text.

One would expect from peridotite of the above character a seismic velocity for Vp near 8 km/sec, which is in good agreement with observed velocities from below the Mohorovičić at sea. Other rocks, perhaps eclogites or rocks comparable to stony meteorites, might produce similar velocities but no such xenoliths as are found in oceanic volcanoes. Continental volcanoes do have a variety of different types of xenoliths as well as peridotites which are identical to those from oceanic volcanoes. But in the case of continental volcanoes, samples of any rock type occurring in the continental crust may be found as foreign inclusions. The conclusion cannot be avoided that the rock forming the xenoliths must be the material from below the Mohorovičić under the oceans, and it seems probable from negative evidence that it is the only rock type present. On the basis of what is known of this rock's physical properties, it could make up the entire mantle to the core. Not enough is known of its properties nor of the physical constants of the earth's interior to make the above statement any more than a presently possible hypothesis.

Consideration of material lying between the Mohorovičić and the unconsolidated sediments remains. Commonly this is considered to be largely basaltic in composition. The only direct evidence, aside from seismic velocities, to substantiate this belief are: the small angular gabbroic fragments found by Duplaix and Cailleux (1952) with the serpentinized peridotite fragments in the Romanche trough; and the gabbroic and basaltic fragments along with serpentines dredged from fault scarps on the mid-Atlantic Ridge by Ewing, *et al.* Inasmuch as the above fragments come from scarps which also expose the ultramafic rocks from below the Mohorovičić, it seems reasonable to suppose that the gabbroic and basaltic debris represent the immediately overlying material. The fact that basaltic cobbles and fragments are found at many places on the ocean floor is suggestive but not acceptable evidence, inasmuch as these no doubt come from basaltic volcanoes which have cut through the crust and which are not necessarily the same material that makes up the layer in the crust considered here.

The total thickness of sea floor sediments which have been determined is less by a factor of 3 to 5 than previous estimates based largely on rates of sedimentation (Kuenen, 1946). This naturally raises the question whether some consolidated sedimentary rocks having seismic velocities near basalt could be included in the layer described above as basalt. Cherts and massive limestones or dolomites could have such velocities and are not unlikely as deep sea sediments. Such rocks are not among those dredged from oceanic fault scarps, therefore evidence, so far as it goes, is against the postulate.

It is possible that some serpentinized peridotite such as that found on the mid-Atlantic Ridge is present in the "basaltic" layer. Seismic velocities in two samples of such material were measured in the laboratory for the writer by E. C. Bullard; measurement gave for Vp 5.7 and 6.3 km/sec at atmospheric pressure. These velocities might be 5 to 10% higher at pressures consistent with their depth within the crust.

Balance of Crustal Columns. In a recent paper the writer (1954) tried to estimate the pressures at 40 km under both oceanic and continental crustal columns. The thicknesses of various layers and of probable rock types included in them were estimated from seismic data and from petrological inference. Appropriate densities, with due allowance for compressibility and thermal expansion, were attributed to the layers. Inasmuch as there is a great deal of inference that goes into such estimates and since there is comparatively little experimental data at both high pressures and temperatures, the values given cannot be rigorously defended. Recently density determinations on samples of peridotites which are thought to come from below the Mohorovičić were made; they were found to be somewhat higher than those previously estimated. Four typical samples gave density values of 3.348 g/cc ± .005. A peridotite cited by Daly (1946) has a density of 3.35 g/cc at room temperature and pressure but 3.28 g/cc at 1500° C and 30,000 bars. From this the density of the peridotite under consideration here is estimated to be 3.31 g/cc at 40 km. It is important to note that in the uppermost part of the mantle the density should be decreasing slightly from the top of the mantle downwards. As the temperature gradient becomes less steep, this trend will be reversed. So little is known of the thermal gradient in depth that one cannot predict the position of this reversal.

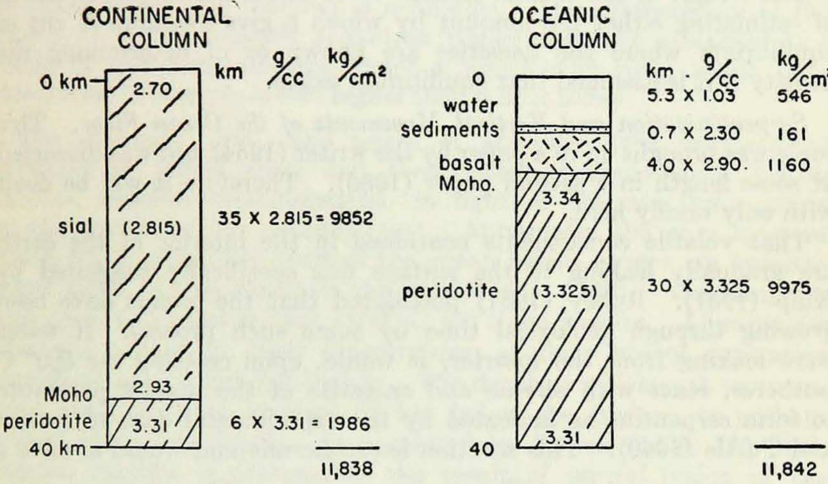

Figure 2. Comparison of layers, densities and masses of typical oceanic and continental columns.

In Fig. 2 the continental and oceanic columns down to a depth of

40 km are compared. With present seismic data and information on densities of the oceanic column, the pressure at 40 km cannot vary much from the 11.8×10^3 kg/cm^2 as given. The continental column is less certain. The average density of the continental crust probably lies between the limits 2.78 and 2.84. At 40 km these limiting densities would give pressures from 11.7 to 11.9×10^3 kg/cm^2. This indicates that the oceanic and continental columns are almost in balance, if not exactly in balance. Assuming an exact balance, the figure 2.815 g/cc is obtained for the density of the continental crust, the value used in Fig. 2.

The weight of the crustal column to 40 km is a convenient means of estimating either the amount by which a given column is out of equilibrium where the densities are known or of determining the density if it is assumed that equilibrium exists.

Serpentinization and Vertical Movements of the Ocean Floor. This topic was brought up in a paper by the writer (1954) and was discussed at some length in a second paper (1955). Therefore it will be dealt with only briefly here.

That volatile constituents contained in the interior of the earth are gradually leaking to the surface was specifically suggested by Kulp (1951). Rubey (1951) postulated that the oceans have been growing through geological time by some such process. If water were leaking from the interior, it would, upon crossing the 500° C isotherm, react with olivine and enstatite of the mantle peridotite to form serpentine as indicated by the experimental data of Bowen and Tuttle (1949). This reaction is exothermic and would involve a

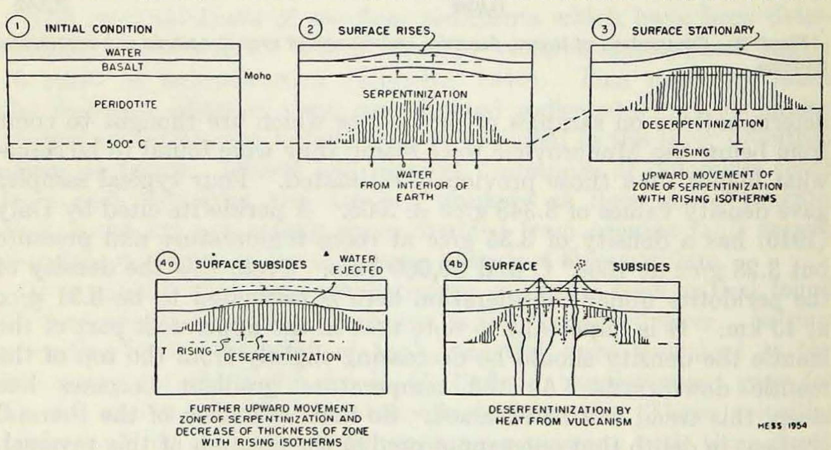

Figure 3. Diagrams to indicate how serpentinization and deserpentinization of mantle peridotite might cause vertical movements of sea floor.

volume increase of approximately 25%. The volume increase is approximately equal to the volume of the water added.[1] The operation of the process, indicated in Fig. 3, will not be elaborated on here. Such features as the mid-Atlantic Ridge, mid-Indian Ocean Ridge and several oval-shaped plateaus more than a hundred kilometers across in the North Pacific and Indian Oceans might be attributed to water leakage from the interior of the earth under these areas and to consequent serpentinization with volume increase above the 500° C isotherm. Rise of the 500° C isotherm as a result of injection of basaltic magma, or perhaps convective overturn of the mantle, would cause deserpentinization and subsidence of the topography. In other words, the reaction is reversible. The submergence of the guyots of the mid-Pacific Mountain Range might be explained as a result of deserpentinization under a mid-Pacific ridge which once stood some thousands of feet higher than it does today.

The Andesite Line. The origin of andesites (the predominant extrusive of island arcs) and their intrusive equivalents, quartz diorites, requires reconsideration in light of the new information on the nature of the oceanic crust. Apparently the only magmas which cut through the crust of the ocean basins proper are basaltic, either alkali olivine basalt or tholeiite (Tilley, 1950). The temperature upon extrusion is near 1100° C for these basalts. Allowing for adiabatic expansion, their temperatures at their site of generation must have been somewhat higher. The depth at which such temperatures exist must be at least 60 km below the surface, or perhaps several times this depth. As suggested by Bowen (1928: 315–320), basaltic magma is presumably the result of *partial* fusion of the peridotitic mantle, material such as is given in the chemical analyses of Table I. It is unlikely that andesitic magma could be formed directly by partial fusion of peridotite, and its absence as a primary magma in oceanic areas seems to substantiate this view. Partial fusion of basaltic rock would be a chemically satisfactory source for andesitic magma. Basalt of the normal oceanic crust is at much too shallow a depth and hence at too low a temperature to suffer partial fusion. Apparently only in connection with island arc deformation is the basaltic layer downbulged to a sufficient depth to generate andesitic magma. Even in this case the downbulging must be somewhat greater than that which has been indicated thus far by seismic work over trenches. This, however, is a possibility, as will be pointed out in the succeeding section of this paper.

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[1] At temperatures up to 700° C, water reacting with enstatite would produce talc with a 10% volume increase.

With a thick crust under island arcs, as was generally postulated before the advent of seismic work at sea, it was possible to derive andesite by partial fusion of this crust or by contamination of basaltic magma passing through such a crust. Consequently it was concluded that andesitic volcanism indicated that island arcs represented the seaward boundary of continental crustal conditions, i. e., the outer margins of continents. This concept is no longer tenable. An oceanic type of crust has been found between the arcs and the continents and inside such seas as the Caribbean. The andesite line does not represent the continental margin. Rather, andesite will be produced where deformation is sufficiently strong to bulge the basaltic layer down to sufficient depth to cause partial fusion. For some as yet unexplained reason, such deformation commonly takes place in the oceans not far from continental margins, but if it were to take place in midocean, a similar result could be expected.

Gravity Anomalies and Island Arcs. The belt of huge negative gravity anomalies found in island arcs, as explained by Vening Meinesz as well as by Umbgrove, Kuenen, Griggs, Hess, and others, resulted from downbuckling or downbulging of the upper granitic crust which was then considered to be about 25 km thick. The mass deficiency of the downbulged granitic material as compared to the supposed basaltic material on either side of it was sufficient to account for the size of the anomalies and for the shape of the anomaly curve. In island arcs the mass distribution proposed in the above hypothesis is now known to be incorrect, as pointed out by Ewing and Worzel (1954) and Worzel and Ewing (1954). Substitution of new values for densities and thickness of layers, as required by recent seismic data, results in a new picture for the cross-section through the negative anomaly belt over trenches. The dimensions are changed, but qualitatively the structure may remain much the same.

An excellent topographic and seismic survey was made over the Tonga Trench on the Capricorn Expedition of Scripps Oceanographic Institution. The seismic profile was reported on by Raitt, *et al.* (1954). It shows a normal basaltic layer about 5 km thick away from the Trench which thickens to an observed 10 km in a profile run along the bottom of the Trench. The depth of the basaltic root under the Trench, however, may actually be considerably greater, inasmuch as the measurement may represent the slant distance to the Mohorovičić sideways at an angle of perhaps 45°. The vertical depth to the Mohorovičić could be much greater, as shown in Fig. 4 and as suggested by the presence of andesitic volcanism in the island arc to the west. The critical point is that the basaltic layer does thicken and hence the structure is to be explained by lateral compression. Sedi-

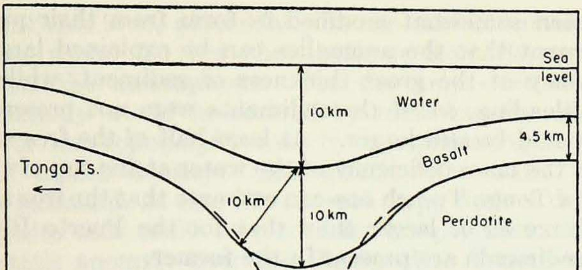

Figure 4. Sketches to indicate hypothetical structures of Tonga and Puerto Rico trenches. Vertical exaggeration about 2.5 ×. Data for construction of sketches taken from authors indicated, but writer takes responsibility for the interpretation as given.

ments are virtually absent from the floor of the Trench. Gravity data for this Trench, not obtained thus far, would be exceedingly interesting to have. However, the mass deficiency under the Trench profile may be estimated; it is at least as large as that under the Puerto Rico Trench, so one might expect similar or larger gravity anomalies (Fig. 5).

Worzel and Ewing (1954) have given excellent gravity data for the Puerto Rico Trench as well as a partial seismic profile. Their analysis of the mass deficiency based on the free air anomalies and computed from Vening Meinesz's tables is most enlightening. While the depth to the Mohorovičić could not be seismically determined under the Trench, an approximate thickness for the sedimentary fill was obtained so that the remaining thickness of the basaltic layer may be estimated from the gravity data. Fig. 4, which shows a profile through the Puerto Rico Trench based on the Worzel-Ewing data, has been somewhat modified in form from their presentation. Their statement that the anomalies can be explained largely by the mass deficiency of the great thickness of sediment, while true in a sense, is misleading, for if the sediments were not present then the anomalies would be still larger. At least half of the free air anomaly results from the mass deficiency of the water at the top of the column. In the case of Tonga Trench one can estimate that the free air anomaly will be as large as or larger than that for the Puerto Rico Trench, though no sediments are present in the former.

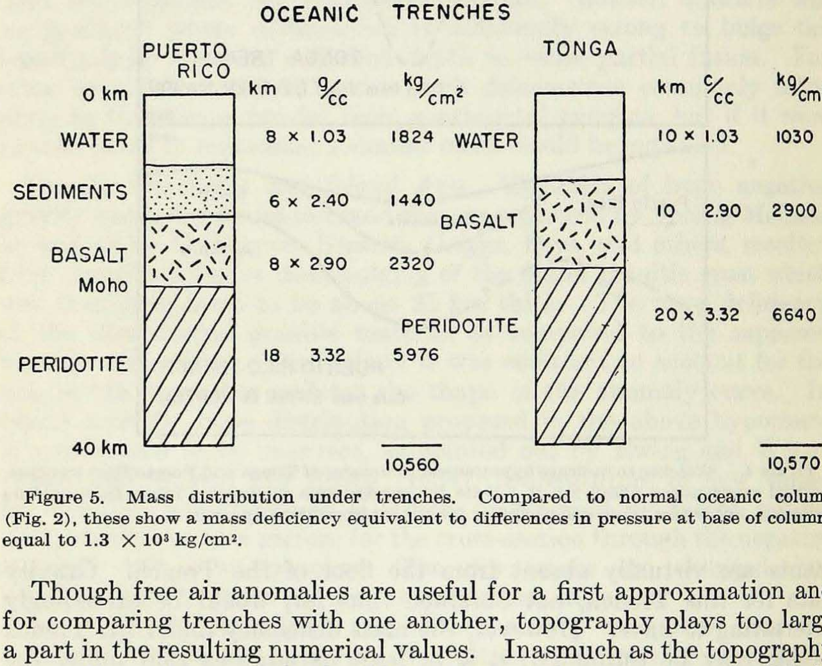

Figure 5. Mass distribution under trenches. Compared to normal oceanic column (Fig. 2), these show a mass deficiency equivalent to differences in pressure at base of columns equal to 1.3×10^3 kg/cm².

Though free air anomalies are useful for a first approximation and for comparing trenches with one another, topography plays too large a part in the resulting numerical values. Inasmuch as the topography is usually well known, it should be eliminated so far as is possible in order to get information on the deeper structure. A type of modified Bouguer anomaly might be devised to do this. Using a datum plane of 3000 fathoms, the mass deficiencies of depressions below this datum or excesses above it could be computed by using a suitable density for the oceanic materials; thus the effects could be removed from the observed gravity value. Various isostatic anomalies in which the effect of topography and compensation are introduced are useful if not essential to understand the meaning of the gravity data. Objections have been made to isostatic anomalies at sea on the basis that the compensation element in them is purely fictitious.

Granted that this is so, particularly in the case of trenches, they are none-the-less useful in that they indicate how the real structure departs from the assumptions. For the area over a trench, the isostatic anomaly would be derived by removing the effect of mass deficiency of the topography and by compensating in depth with material of higher density. Geologically this would probably be impossible inasmuch as there is no rock type with a density higher than peridotite that could be placed in this position. Computation of the isostatic anomaly over the Puerto Rico Trench confirms this in showing that it is not compensated and hence is out of isostatic equilibrium, at least locally. If it is not compensated locally, other types of isostatic anomalies could be used to find out whether it is compensated regionally and over how large a radius.

The same conclusion of lack of isostatic equilibrium of the trenches could be reached from an analysis of the seismic data. Comparison of the normal oceanic column (Fig. 2) and trench columns (Fig. 5) shows a difference in pressure at the base of the columns amounting to more than 1×10^3 kg/cm^2. Considering the large horizontal area of the trenches, it is quite impossible that the crust could be this far out of isostatic equilibrium *unless a force were acting on it to keep it out of balance.* The value of approximately 1×10^3 kg/cm^2 is a measure of the vertical component of that force. This could mean a compressive force acting tangentially of at least three times this amount. If this force were not acting, then the trenches would rise to the equilibrium position. In the case of the Puerto Rico Trench it might be expected to rise from 4300 fathoms to form a ridge about 1250 fathoms below sea level. This would produce a topographic feature similar to the Barbados Ridge, but unlike the latter it would not then have a large negative isostatic anomaly above it. The Barbados Ridge must represent a great thickening of the sedimentary and basaltic layers so that it is still almost as much out of isostatic equilibrium as is the Trench. In essence it is developing a downbulge more nearly comparable in size and thickness to the original picture presented by Vening Meinesz. Presumably continued deformation and thickening will eventually produce from such a structure enough sialic material to support an alpine type of mountain range when the forces acting on it die out.

The structural interpretation of geophysical data often cannot be made in complex areas without reference to geological history. In the case of the Puerto Rico Trench, it was initiated as a structure at some time after the Paleocene. Previous to that time a trench probably existed trending ESE along the south side of Puerto Rico. Puerto Rico itself was on the crest of an island arc which probably was concave toward the NE and which contained numerous active volcanoes along its length. This volcanism of Late Cretaceous and Paleocene built up a huge pile of lava, agglomerate and tuff which resulted in a greatly thickened crust under the area of the present island. The sediments and volcanics in the trench to the SW were strongly deformed, probably in the early part of Late Cretaceous, and were converted to schists, the extension of which are now seen to crop out in the Cordillera Central of the Dominican Republic and also in the southwestern corner of Puerto Rico. These geological circumstances strongly affect the interpretation of the southern half of the Worzel-Ewing profile. This information was not available to them when they presented their results.

Evolution of an Island Arc into an Alpine Mountain System. This concluding section is frankly speculative. It is advanced to direct attention to items which may give critical evidence on island arc structure and development.

The development of island arc structures into alpine-type mountain structures is a well substantiated hypothesis. The evolution is a much longer and more complex process than this writer (Hess, 1938) originally envisioned. The Tonga Trench may be pointed to as the first stage in development. Here, if the deforming forces were to die out, the Trench would disappear and a gentle ridge 500 to 1000 m high on the sea floor would take its place.[2] The thickened basaltic layer would then be floating in isostatic equilibrium. The Puerto Rico Trench has not gone so far in its evolution, but it has received a huge volume of sediments. Large islands are nearby to provide a source of sediments, and the bottom topography is such that turbidity currents which carry these sediments drain into the Trench. There is no evidence that the sediments in it have been deformed as yet. Inasmuch as andesitic volcanism occurs in the arc to the west of the Tonga Trench but not in relation to the Puerto Rican, one might postulate that the basaltic root under the Tonga Trench is deeper.

The next more advanced stage may be represented by the Barbados Ridge. It is still far out of isostatic equilibrium. A downward bulge, probably of sediments underlain by metamorphosed sediments and basaltic material, altogether perhaps 30 km thick, has developed, judging from isostatic anomalies. Active volcanism in the Lesser Antilles indicates a deep root. If the Barbados Ridge were relieved from compression, it would rise to form a low island chain with the

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[2] The rise necessary to bring the weight of the crustal column back to 11.8×10^3 kg/cm^2 at 40 km depth assuming a minimum thickening of the basaltic layer (10 km).

rudiments of alpine structure. Probably it would not, if arrested at this stage, form a high mountain range. The islands of Hispaniola and Cuba probably represent just the situation speculatively proposed above for the Barbados Ridge development. To produce high mountains, much more crustal shortening and a much larger downbulge would be required. One may question whether island arcs starting on a true ocean floor will ever develop beyond the stage of a Cuba or Hispaniola in one mountain-building series of episodes. Many island arcs of the past which developed only to the early trench stage may today form rather inconspicuous topographic forms on the ocean floor.

With the above reasoning, one may ask how one would ever develop a mountain system such as the Himalayas. The clue to this seems to be given by following the Antillean chain southward and westward into the Cordillera along the northern coast of Venezuela. Where island arc-type of deformation impinges on the edge of the continent, the thin sialic crust may be downbulged in exactly the manner postulated formerly by Meinesz for the negative strip of island arcs. The great Alpine-Himalaya chain probably began along a mediterranean of oceanic character and transgressed in places on the border of a continent. The apparent termination of some continental mountain systems abruptly at the sea may mean that their extensions on the ocean floor are inconspicuous and are perhaps covered at present by sediment, as indicated in the preceding paragraph. This might explain why the early Paleozoic folded mountains seem to disappear at the coast of Newfoundland and reappear in northern Ireland and Scotland. Traces of this might be discovered by an increase in depth to the Mohorovičić along the line joining the two ends.

Finally it should be pointed out again, as the writer has done in the past, that island arc-alpine type of deformation rarely if ever takes place within continents proper which have a normal thickness of sialic crust. The forces may be the same but the reaction to them different. The best example of this type of reaction is the Rocky Mountains of the United States. It is comparatively rare for mountain building to occur deep within continents.

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