Problems of the Upper Mantle and Hawaii as a Site for the Moho Hole[1]

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GEOPHYSICAL DATA PERTAINING TO THE MANTLE

The term "mantle" is a geophysically-derived term believed to have geological significance. As used, it refers to that material lying between the earth's core at a depth of 2900 km, which is also defined geophysically, and that depth at which the velocities of seismic compressional waves increase from values of about 6.5–7.0 km/sec to 8.15 ± 0.5 km/sec. The variations in velocity associated with the mantle are of both a local and regional nature, and in many areas are azimuth dependent. Although the identifying velocity of 8.15 ± 0.5 km/sec may incorporate some bias because of poor measurements, it is significant that out of 316 measurements 223 (71%) lie between 8.0 km/sec and 8.3 km/sec, and that carefully conducted experiments show the same range in values as does the gross sample of data. Anisotropic seismic transmission in the mantle is not uncommon, and can be attributed to selective orientation of the mineral grains. It is not to be confused with boundary slope effects or the effect of progressive changes in heat flow or mantle composition. Regional variations in mantle velocity based on reversed profile recordings are related either to variations in mantle composition or to heat flow. Local variations in velocity may or may not be real and, if real, are probably related to anisotropic transmission. Regional transmission studies such as those based on the GNOME and SALMON underground nuclear explosions, although possibly biased by slope effects due to regional changes in crustal thickness, clearly indicate that the velocity character of the mantle is not uniform beneath the United States, and that the western area has a subnormal mantle velocity probably because of higher heat flow. Similarly, it is found that certain oceanic areas as the Mid-Atlantic Ridge and the East Pacific Rise have a subnormal mantle velocity which can be correlated with heat flow measurements. That there are true regional differences in mantle composition is suggested by oceanic data. The average mantle velocity found in the Pacific Ocean is significantly greater than that found in the Atlantic Ocean, and also greater than that found on the continents. The respective values are shown in Table 1.

TABLE 1.
AVERAGE MANTLE VELOCITY IN DIFFERENT REGIONS

REGION	MEDIAN (km/sec)	RANGE (km/sec)
Pacific Ocean	8.25	7.65–8.7
Atlantic Ocean	8.10	7.65–8.55
Continents	8.12	7.7 –8.5

It is to be noted that the lower limit of velocity values is much the same in all three areas and is associated in most cases with areas known or suspected of having high heat flow. It is not inconceivable that in these areas there may also be mixing or transformations of crust and mantle material that would also lower the mantle velocity. The high upper limit of 8.7 km/sec observed in the Pacific Ocean is not regarded as significant because it is confined to a single measurement.

That there are variations in mantle material with depth is suggested by seismic refraction measurements, which show in some areas evidence for deep layers below the "M" discontinuity having velocity values in the range 8.5–10.0 km/sec. As this deep structure has been reported in various parts of the world, it is probably real, and in view of the heterogeneous nature of the crust which is well established, it is probable that the mantle is also heterogeneous.

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That there may be a relation between the composition of the mantle and the overlying crust is suggested by several lines of evidence. For example, the seismic measurements conducted by the Lamont Geological Observatory during the International Geophysical Year over the Scotian Sea show that the mean velocity and thickness of the crustal layer as well as the velocity of the underlying mantle all decrease as the nose of the Scotian arc is approached. If "blanket" data are considered, and all measurements in the Atlantic Ocean area are considered, it is found that there is a positive correlation between the mean velocity of the crust and the mean velocity of the mantle where there are positive isostatic gravity anomalies, and a slight negative correlation where there are negative isostatic anomalies. There is no systematic relationship between the two quantities where isostasy prevails. On the continents the same relations are observed, except that the correlation slopes are much higher and about equal in magnitude in areas of positive and negative isostatic anomalies. In the Pacific Ocean no appreciable difference in relations as a function of gravity is found, and both the negative and positive isostatic gravity anomaly areas show a slight negative dependence of the velocity of the crust on the velocity of the mantle.

These regional differences between the Pacific and Atlantic oceans are also brought out by the relation between crustal thickness and Bouguer and free-air gravity anomalies. Again using "blanket" data, it is found that, for oceanic depths 5.0–6.0 km in both oceans, the anomalies in the Atlantic Ocean are about 20 mgal more negative than in the Pacific Ocean and the crust is about 1 km thinner. As the depth of water is the same, this implies either a difference in mean crustal density or a difference in mantle density, or a combination of the two. As indicated earlier, the median mantle velocity in the Pacific Ocean is significantly higher than in the Atlantic Ocean, which would imply a higher density for the mantle and, hence, greater density contrast with the crust. To maintain the same bottom elevation under hydrostatic equilibrium conditions with a thicker crust, the density of the crust in the Pacific Ocean must be greater than in the Atlantic Ocean. When one examines mean crustal velocity values, it is found that the values support this hypothesis. This positive correlation between crustal and mantle velocity values strongly suggests that there is a genetic relationship between the crust and mantle. That the mantle and the basal layer of the crust might represent polymorphic phase transformations of the same material, with the depth of the Mohorovicic discontinuity being a function of pressure and temperature relations at depth, has been suggested by Kennedy (1959). Hess (1955) has suggested serpentinization as a reversible process that would also provide a genetic relationship between the crust and mantle.

The most convincing arguments as to the reality of such a phenomenon are the anomalous relations of crustal thickness in areas of crustal subsidence and uplift. For example, the value of crustal thickness determined seismically in Texas, where the crystalline rock basement has been down-warped approximately 7.5 km since late Paleozoic, is about 33 km, which is normal for the surface elevation of 50 m. That the seismic measurement is not substantially in error is indicated by the local gravity anomalies, which show there is essentially complete compensation for the thick column of low density sediments having a theoretical gravity effect of about 80 mgal after allowing for compaction and variations in lithology. As the sediments are either terrestrial in origin or represent shallow water facies, it is probable that the crustal thickness has remained essentially constant, and the progressive down-warping of the surface has been accompanied by a corresponding upward migration of the mantle at the expense of the basal crustal layer to maintain isostatic equilibrium.

Another line of evidence bearing on this problem is the absence of a pronounced crustal root beneath areas of eustatic uplift. On the Mexican Plateau, for example, the seismic crustal measurement at Durango shows the same sub-sea level elevation for the mantle (−41.2 km) as is found at Calgary, Alberta in front of the Rocky Mountain block. Although Calgary is essentially in isostatic equilibrium, as is indicated by both gravity data and its crustal thickness of 43 km for a surface elevation of 900 m, Durango has a subnormal gravity field (−25 mgal isostatic anomaly) and subnormal crustal thickness (43.4 km) for its surface elevation of 2200 m. The same anomalous relations are noted in the middle Rocky Mountain region, where the seismic measurement paralelling the Continental Divide actually shows a thinner crust than is found in the adjacent High Plains area of Wyoming. This anomalous change in crustal thickness with surface elevation here is also substantiated by phase velocity dispersion studies of the crust (Meyer, Steinhart, and Woollard, 1958; Ewing and Press, 1959; Steinhart and Meyer, 1961; and Woollard, 1962). As both the plateau of Mexico and the Rocky Mountain area have been subject to eustatic rise since Miocene time, it appears that this uplift has been the result of crustal expansion without any significant deepening of the crust-mantle interface, and without any observable decrease in the velocity of the mantle such as is apparent in the Basin and Range area from regional seismic transmission studies. These relations all suggest reversible exchanges of mantle and crustal material with an appreciable difference in volume and density between the two phases and, as indicated, would explain eustatic uplift and also crustal subsidence such as is noted in the Gulf Coastal Plain without any observable warping of the crust-mantle interface. The tectonic implications of the Kennedy and Hess hypotheses, however, are different. One would have changes in surface load governing the thickness of the crust and the depth to the crust-mantle interface; and the other has movement of surface load responding to changes in surface elevation created by changes in crustal thickness as a result of hydration or dehydration effects at depth.

Summary

The geophysical evidence relating to the mantle can be summarized as follows:

1. The mantle does appear to vary in its physical properties on a regional basis.
2. There is evidence for variations in the structure and composition of the upper mantle with depth.
3. The mantle in many areas is characterized by anisotropic seismic transmission.
4. The physical properties of the mantle are influenced by anomalous heat flow.
5. There is evidence that the physical properties of the basal layer of the crust are related to those of the underlying mantle.
6. There is evidence that the basal layer of the crust and mantle might represent different phases of the same material which is controlled either by static pressure and temperature conditions at depth or the addition or subtraction of water at depth. Either mechanism could result in an increase or decrease in the volume of crustal material with consequent crustal uplift or subsidence.
7. Gravity data in conjunction with seismic data suggest that isostasy is a real phenomenon for all crustal blocks having a radius of 100 km or more, and that apparent regional departures from isostasy are related to the mean density of the crust rather than to any actual departure from hydrostatic equilibrium between the crust and mantle. The sign of the anomalies appears to be due to the proximity effect, whereby the effect of the near-surface mass distribution predominates over that of the deep-lying mass distribution providing isostatic compensation.
8. A process whereby the crust-mantle interface and changes in surface elevation, mass transfer, and tectonic processes involving changes in crustal mass and volume are automatically accommodated through a reversible crust-mantle transformation would resolve the problem on how isostasy is maintained. Although the resulting mass distribution does not allow for the gravitational effect of sub-mantle variations in mass, the gravity contribution from such deep-seated mass distributions may be nil. As yet there is no evidence that velocity values greater than 8.5 km/sec indicate any increase in density.

THE MANTLE AS A GEOLOGICAL ENTITY

The geological identification of the mantle is dependent upon laboratory studies of the physical and chemical properties of rocks. Not only must the rock material chosen satisfy the seismic velocity values noted, but it must also provide a density contrast with the crust that will yield the observed change in crustal thickness with surface elevation and also satisfy the observed change in gravity values with elevation and isostasy.

When one examines the relation between seismic velocity values and density values for different rocks, as determined in the laboratory under surface conditions and high confining pressures, the only rock material that appears to satisfy the above restrictions is a rock composed predominantly of olivine having a density of about 3.33 gm/cc. Eclogites have too high a density and too low a seismic velocity, and no other rock types having the requisite density, such as pyroxenite, appear to have the required high velocity. The companion velocity-density relations for the crust suggest a continental crust having a surficial layer with an observed density of 2.74 gm/cc (from 1158 samples of crystalline rock distributed over North America) and an observed seismic velocity of 5.5 km/sec at the surface increasing to 6.15 km/sec at a depth of 3 km because of the compressibility effect on the modulus of rigidity with no appreciable change in density, and varying linearity through the relations for gabbroic rocks under pressure to mantle relations defined by a velocity of 8.15 km/sec and a density of 3.33 gm/cc which correspond closely to the properties of dunite under high pressure.

This conclusion concerning the mantle agrees with that of Hess (1955, 1962) who, in a recent report (1964) on the serpentinite in the AMSOC core hole in Puerto Rico, concludes that the worldwide similarity of olivines, and of reconstituted serpentines to yield a similar chemical composition, provides a universal rock type that will satisfy not only the requirements of the mantle, but also that of a source rock providing the structure and composition of the oceanic crust. Hess postulates that "layer 2" of the crust is basalt derived by magmatic differentiation from an olivine-rich mantle rock through volcanism, and that "layer 3" is serpentinite formed by the hydration of dunitic mantle material.

There is, however, one problem connected with Hess' model; namely, how to get the required crustal density stratification and observed seismic structure without having the "layer 2" as full of holes as Swiss cheese. The work of Moore of the U. S. Geological Survey (in press) shows that "fresh" submarine basalts increase in bulk density from 2.2 gm/cc at the surface to 2.9 gm/cc when emplaced under a hydrostatic head of 3000 ft, and that at oceanic depths of 5 km the density is 3.0 gm/cc. This change in density with depth of water is due to the decrease in vesicle porosity with confining pressure. Laboratory studies of the seismic velocities associated with these whole rock basalts likewise indicate an incompatible velocity of about 6.6 km/sec. If the "layer 2" crustal layer is basalt, its low seismic velocity of 4.0–4.5 km/sec would require it to be now mostly serpentine or having a high porosity. The latter could be affected by having it emplaced under subaerial conditions or made up of pillows having sufficient inter-pillow voids to give the required low velocity. Normal basalts having a velocity of about 4.5 km/sec have a density of around 2.35 gm/cc.

The basal crustal layer postulated by Hess to be serpentinite could well exist. Although only one serpentinite tested to date has the requisite velocity of about 6.5 km/sec and density of 2.8 gm/cc under a confining pressure equivalent to about 1.5 kilobars, the fact that such material does occur (Birch, 1964) is sufficient argument to prove that the hypothesis is not an unreasonable one.

Using the velocity-density relations defined earlier (Woollard, 1962), the mean density of the crust on the continents based on seismic measurements is 2.86 gm/cc, giving a density contrast between the crust and mantle of 0.47 gm/cc. In the Pacific Ocean the mean density of the crust is calculated to be 2.90 gm/cc. The Atlantic Ocean crustal data show two groupings, 2.80 gm/cc and 2.90 gm/cc, with an average value similar to that found on the continents.

The fact that these regional differences in derived crustal and mantle density will affect the thickness and depth of the mantle has already been remarked in connection with the difference in crustal thickness observed in the

Pacific and Atlantic oceans for the same abyssal depths of water. Presumably, there will also be a difference in the magmas generated in the two areas and in the types of volcanic material erupted. The data bearing on this point are not too conclusive, as magmatic differentiation with gravity separation of early crystallized heavy mineral constituents such as olivine in the magma chamber can lead to differences in the lavas appearing at the surface. However, this subject will be deferred for the moment, and that of the relation between crustal thickness, surface elevation, the density contrast between the crust and mantle, and gravity relations will be considered.

If the data for seismic determinations of crustal thickness in North America are selected on the basis of areas where the gravity data indicate regional isostatic equilibrium within ± 10 mgal, and the depth of the Moho is plotted as a function of surface elevation, the following linear relation is found:

$Hc = -(31.7 + 6.0\ h) \pm 6$, where Hc is the depth of the Moho below sea level in kilometers, and h is the surface elevation above sea level in kilometers. This formula, however, will not apply to oceanic areas unless the water column is reduced to equivalent crustal material of 2.86 gm/cc density to obtain a synthetic rock surface elevation. That the above formula will satisfy closely observed gravity data can be shown by example.

Under isostatic equilibrium conditions, the free air anomaly in general increases with elevation in accordance with the formula $F = -3 + 7.5\ h$, where h is the regional surface elevation in kilometers. This results from the increase in the depth of the compensating mass with elevation and crustal thickness and the integration of the topographic effect from more rugged terrain which increases with elevation. The effect of distant topography and compensation likewise changes with elevation, in accordance with the formula $C = 13.7\ h$, where h is the surface elevation in kilometers. The local compensation (crustal root) for an area, therefore, is approximated by the equation:

$$\Delta R = \frac{-BA - F + C}{41.85 \times \Delta\sigma}$$

where ΔR is the crustal root in kilometers greater than that at sea level; BA is the Bouguer anomaly mass correction computed using a mean crustal density of 2.86 gm/cc for the crustal section above sea level; F, the free-air anomaly change with elevation; C, the effect of distant topography and compensation; and $\Delta\sigma = 0.475$ gm/cc to obtain agreement with the free board to root ratio of 1:6, as determined empirically.

For an assumed surface elevation of 2000 m, the Bouguer anomaly mass correction is (BA) $= 2 \times 41.85 \times 2.86 = 239$ mgal. The free-air effect (F) $= -3 + 7.5 \times 2 = 12$ mgal. The distant compensation effect (C) $= 13.7 \times 2 = 27$ mgal.

$$\therefore \Delta R = \frac{-239 - 12 + 27}{41.85 \times .475} = \frac{-224}{19.87} = 11.3 \text{ km}$$

On the basis of elevation alone, $\Delta R = 6.0\ h$, where h is the surface elevation in kilometers. For h = 2000 m, $\Delta R = 6.0 \times 2 = 12.0$ km.

The agreement is excellent, considering the approximate nature of the equations defining the free-air effect and that for distant topography and compensation, the uncertainty in defining the empirical relation between crustal thickness and elevation, and the unknown contribution of structure in the upper mantle. A crust having a density of 2.86 gm/cc with a mantle having a density of about 3.33 gm/cc, as derived from seismic velocity-density relations, reasonably satisfies both isostasy and known gravity relations to elevation. It constitutes a major argument for the mantle's having a composition comparable to that of dunite.

Let us now turn our attention to the geologic evidence offered by volcanic eruptives. It has been known for some time that the basaltic lavas forming the Hawaiian Islands differ from those of most other oceanic islands in that they are predominantly tholeiitic with a very low percentage of potassium. It has also been established that the alkalic basalts, trachytes, and andesites found in Hawaii are late stage eruptives, and probably are differentiates of what was originally tholeiitic basaltic magma. The predominant alkalic basalts found in the Society Islands, Samoa, Fiji, and other islands presumably could also represent magmatic differentiates of an original tholeiitic magma. Alternate explanations are: (a) there are regional variations in the chemical composition of the mantle, (b) the composition of basalt is a function of partial melting of the mantle, or (c) of the depth at which the magma is generated. In connection with this hypothesis, the laboratory investigations of Yoder and Tilley (1962) suggest that the composition of the magma can be a function of pressure and temperature, and that alkalic basalt represents a deeper, higher pressure environment than does tholeiitic basalt.

To investigate this problem the writer and Gordon A. Macdonald started a program of integrated geophysical and geological studies in the Hawaiian Islands and Samoa in 1963 under the sponsorship of the National Science Foundation. Although this study has not been completed, preliminary results which will be presented in this report suggest that magmatic differentiation best explains the relations noted in Hawaii and probably Samoa also. On other islands, such as the Line Islands group, gravity data suggest that the primary magma extruded was alkalic, but there is no clue as to the depth of origin. The only actual data bearing on this point are the relations noted in Japan by Kuno (1959), who found that the alkalic basalts are associated with zones of deep-focus earthquakes and the tholeiitic basalts with shallow-focus earthquakes. If there is a relation between earthquake focal depths and magma generation, and there does appear to be such a relation in Hawaii with magma supplying present active vents originating from about 60 km, Kuno's observations and the Hawaiian data both appear to support the findings of Yoder and Tilley. With regard to partial melting Engel and Engel (1964), in an excellent review study of oceanic basalts, note that this implies a mantle that is even more deficient in radiogenic elements than is tholeiitic basalt. These investigators, on the basis of their comprehensive study of basalts in all oceanic areas, conclude that deep-lying oceanic basalts in general are tholeiitic; that they are all remarkably similar in composition; and that, since their volume is about a thousand times greater than that of alkalic basalts, the alkalic basalts are probably magmatic differentiates of tholeiitic magma.

Thus, the geologic evidence for the composition of the mantle from studies of basalts is not conclusive, and even may be said to be contradictory. The writer's approach to the problem has been through geophysical studies. As tholeiitic basalt has a higher density than alkalic basalt, there should be a real difference in the gravity field associated with primary volcanic pipes supplying the different lavas. On the assumption that these pipes were filled with essentially undifferentiated mantle material in the early stages of intrusion, when the bulk of the lavas was being rapidly extruded and the bulk of the volcanic pile was being developed, as noted recently off Iceland, and that these pipes were sealed off at the top soon after the external pressure was sufficient to develop intermittent volcanism with subsequent eruption via flank rifts developed by doming and fracturing of the volcanic pile or through secondary vents, the primary pipes should contain a substantial sample of the primary magma with little or no differentiation at shallow depth. Certainly the field relations and geophysical measurements on Oahu suggest such a history. On the island of Oahu the two primary pipes whose caldera lie on opposite sides of the island at or close to sea level are marked by local gravity anomalies of about +110 mgal (+310 mgal absolute Bouguer). Later vents, such as Koko Head and Diamond Head, have no appreciable gravity effect, although the bulk density of the surface flow material is only 2.3 gm/cc. The rift flows forming the Koolau Mountains, representing an intermediate stage in the volcanic history of the island, are marked by intermediate gravity anomaly values of about +50 mgal. Somewhat similar conditions are noted on the island of Hawaii, where there is still active volcanism. All of the primary pipes, such as Mauna Kea, Mauna Loa, Kohala, Hualalai, and the present active pipe at Kilauea, are marked by local gravity highs of about +100 mgal. All stages of eruptive history are represented. Mauna Kea is dormant; Mauna Loa, the principal source of lava in the recent past, erupts only periodically and mostly through flank fissures; and Kilauea represents an active, intermittent volcanic caldera. Seismic earthquake focal depths suggest that Kilauea draws its magma from a depth of about 60 km and, as with all other major Hawaiian volcanoes, the late stage lava is now alkalic.

The high gravity anomalies reported by Strange, Machesky, Woollard (p. 350, this issue) for Oahu and by Strange et al. (p. 381, this issue) for the Hawaiian Islands, as a whole, can only be explained by high density rock material having a density of about 3.1 gm/cc coming essentially up to the surface. Seismic refraction measurements in the old Koolau caldera near the town of Kailua on Oahu (Adams and Furumoto, p. 296 in this issue) show that here there is material with a seismic velocity of about 7.0 to 7.6 km/sec at a depth of about 4000–6000 ft. This is similar to the velocity of 7.6 km/sec observed for what may be the mantle at a depth of 6 km on a seismic refraction line along the north shore of Oahu paralleling the Koolau Mountain Rift zone. In addition, deep reflections from about 12,000 ft were obtained on the west side of the Koolau caldera which could represent an inter-crustal magma chamber. On another seismic-refraction line paralleling the south shore of Oahu, the mantle has a velocity of about 9.0 km/sec at a depth of about 23 km. Thus, there is good evidence for mantle-like material at shallow depth in the old Koolau pipe on Oahu. However, this pipe, as well as all others (Malahoff and Woollard, in a forthcoming issue of *Pacific Science*), is characterized by marked local magnetic anomalies, and there is a problem as to the nature of the pipe material. Certainly one would not expect dunite.

In Samoa the gravity measurements likewise show a local gravity high of the same magnitude and absolute value (+300 mgal Bouguer) over the site of the ancient caldera defined geologically, with little gravity effect over the later volcanic pipes. These data, therefore, suggest that the alkalic basalts present are the results of magmatic differentiation, and that they constitute a superficial cover over earlier tholeiitic basalt.

Gravity observations on the Line Islands, however, do not bear out the above relations. The local anomaly values show no pipe effect and have absolute Bouguer values of less than +200 mgal. This is true on Washington, Christmas, Palmyra, and Fanning islands. Johnston Island, which lies on the extension of the Line Island Ridge, however, does have values that get up to about +270 mgal absolute Bouguer. The relations along the Line Island Ridge, therefore, are variable, and either reflect a difference in pipe material, or extreme variability in the degree of differentiation that has taken place in the pipe, or else marked differences in the size of the pipes or depth of the primary material. To some extent similar results are found in the Hawaiian Islands, as on Niihau there is no pronounced pipe effect, and the Bouguer anomalies do not exceed 290 mgal.

In this connection, it is of interest that the gravity values on Bermuda, while showing a smaller local anomaly than on Hawaii (+80 mgal), are higher on an absolute scale (+355 mgal Bouguer) (Woollard, 1954).

By way of contrast with these results, gravity studies of calderas of andesitic volcanoes in Japan all show the pipe area to be defined by a pronounced gravity minimum of 25–30 mgal. A similar relation is observed over granite intrusions on the continents, and the recent report on the AMSOC hole in Puerto Rico (Bromery and Griscom, 1964) shows a local minimum of 20 mgal over a serpentinite body that was once a high density peridotite. Hess (1964) feels that the magma in the latter case originated within the mantle rather than in the crust. Granite presumably originated within the crust during mountain orogeny. Andesitic magmas possibly could be generated in the mantle, as suggested by laboratory studies, but as yet there are no corroborating data other than earthquake foci relations.

Summary

The geologic data taken in conjunction with physical and geophysical data indicate the following:

1. The mantle, in general, appears to be similar to dunite, with seismic velocity of 8.15 km/sec and a density of 3.33 gm/cc.

2. The mean density contrast of the mantle and crust is 0.475 gm/cc, giving a free board

to root ratio of 1:6 for conditions of hydrostatic equilibrium.

3. The changes in crustal root for changes in surface elevation based on the above ratio can be reconciled closely with gravity data for changes in surface elevation, assuming isostatic conditions.

4. Tholeiitic basalts appear to be derived directly from mantle material which rises with possible differentiation but little change in physical properties to within a few thousand feet of the surface in primary volcanic pipes on many oceanic islands.

5. Tholeiitic basalts predominate over alkalic basalts by a factor of 1000:1.

6. The volcanic history of the Hawaiian Islands suggests a progressive differentiation of flow material from tholeiitic basalt to trachyte and andesite with time.

7. Mantle-like material is trapped at shallow depth in all primary pipes along the Hawaiian Swell and also in Samoa.

8. Presumably the mineralogy of this trapped mantle-like material is not the same as that existing in the mantle, since it recrystallized under low pressure and temperature conditions and lost certain constituents through eruption and gaseous dissemination into the surrounding rocks.

9. All oceanic islands do not appear to be characterized by tholeiitic basalts, and there is no evidence on many islands for primary pipes containing mantle-like material; the pipes have either a lower density rock filling, or there is no density contrast with the surrounding flow material.

10. A firm case cannot be made for variations in mantle material from geologic data, although geophysical data suggest that such is the case.

11. A dunitic mantle could provide an adequate source material for the oceanic crust if the basaltic upper layer either has a porosity of about 21% or contains abundant glass.

HAWAII AS A SITE FOR THE MOHO HOLE

Arguments for drilling to the Moho are many, and range from determining whether it is similar to chondritic meteorites to obtaining a better understanding of the isostatic mechanism. It is not germane to the present report to review these arguments or to discuss their validity. Our purpose is to review the scientific arguments for locating this operation in the Hawaiian area rather than elsewhere. It goes without saying that practical considerations, such as the depth of crust to be drilled, the depth of water, distance from a supply base, logistic support, local weather and sea conditions, labor supply, and other factors affecting costs, and the chances of a successful operation will play a role in deciding the drilling site. Even if all these factors were not equal between two potential sites, there would be other factors of a scientific nature that might well justify the selection of one site over another. The writer believes that these additional scientific benefits in the Hawaiian area make it the logical site for the proposed hole to the mantle. Some of these have been touched on in the previous discussion. However, before taking these up, the practical considerations will be reviewed briefly.

Depth of the mantle

The seismic crustal measurements in the vicinity of Hawaii by Shor and Pollard (1964) show that about 125 miles north of Maui the mantle has a subnormal depth of about 9 km below sea level. This is about 4 km less than the normal depth of about 13 km encountered in the Pacific Ocean for the depth of water (2380 fm), and 3 km less than that commonly encountered in the Atlantic Ocean. As this depth to the mantle has been verified by subsequent seismic refraction measurements made by Western Geophysical Company, it is probably realistic. The question naturally arises as to why the mantle should lie at a subnormal depth here and whether there is some associated factor that will mitigate against normal mantle material being present. From Figure 1, which shows the bathymetry in the area, it is seen that the NSF-recommended site (marked by a cross) lies on the south slope of the Hawaiian Arch and about 50 miles north of the buried extension of the Molokai Fracture zone near where it disappears beneath the North Hawaiian Trench. There is nothing in the bathymetry, therefore,

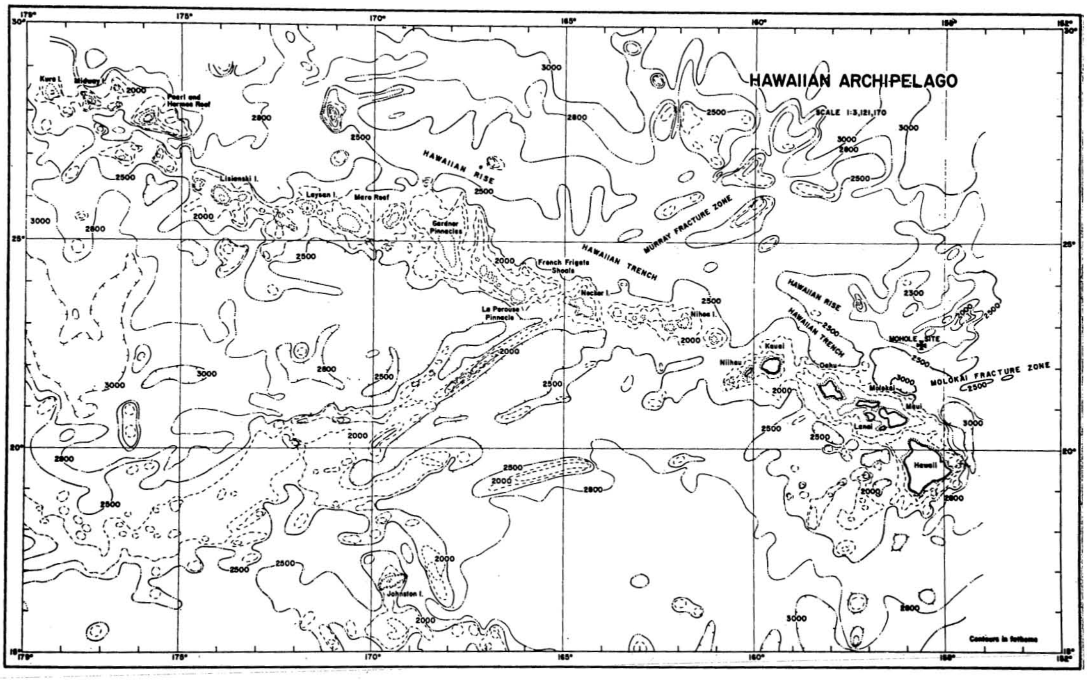

FIG. 1. Bathymetric map of the Hawaiian Archipelago, showing proposed Moho Hole site (*cross*). Contour intervals in 100 fm.

that suggests abnormal conditions at depth. Similarly, when the gravity (Fig. 3 in Strange et al., p. 386 in this issue) and the magnetic (Fig. 2) data are examined, no subsurface abnormalities such as a buried volcanic pipe or crustal faulting are suggested. The shallow depth of the Moho, on the basis of the seismic measurements, results from up-warping of the crust in response to crustal subsidence beneath the Hawaiian Ridge.

Depth of water

The depth of water at the recommended site as indicated is approximately 2380 fm (4350 m). Ship positioning, therefore, probably will have to be maintained acoustically through signals from on-bottom "pingers."

Depth of drilling required

The total depth of drilling required below the sea bottom to reach the mantle, according to the analysis made by NSF of the seismic data, is about 4.6 km, of which about 0.3 km is sediment.

Weather conditions

The area is remarkably free of storms, bad weather, and temperature extremes. The temperature ranges, in general, between 70° and 85°. The prevailing trade winds blow at 12–20 mph from the east much of the year and seldom exceed 30 mph. Because of the constancy in wind direction, a surface current set to the northwest of about 1.0 knot can be expected. Storms, when they do occur, are usually from the south. In these cases, seas will not be high because of the sheltering effect of Maui and resulting short fetch. Average swell runs about 6 ft, and storm waves about 25 ft. Although tsunami waves are to be expected, in the open sea these waves are hardly perceptible and probably no greater than the diurnal tidal change of 1–2 ft.

Seismicity

There is no record of earthquakes in the vicinity of the proposed drilling site. Nearly all the local earthquakes occur along the Hawaiian Ridge and mostly on the island of Hawaii. The magnitude of these earthquakes seldom exceeds IV, and the nearest recorded epicenter to the proposed drilling site lies 120 miles to the south of it.

Auxiliary location control

Both air and sea location systems (Omni, LORAN C, tracking radars) exist in the Hawaiian Islands, which will be of great value in establishing the site location and in maintaining navigational control between the drilling site and shore base once operations are started.

Stability of the water column

Inasmuch as bottom pingers will probably be used to hold positions, variability in mean acoustic velocity presumably could pose a problem. However, maximum annual variation in mean acoustic velocity between the surface and bottom is only about 0.85 ft/sec (approximately 1 part in 5000). Differences in position control due to seasonal changes in water column structure and temperature, therefore, should not exceed 1 m.

Distance from supply base

The recommended site is about 125 miles from Kahului airport on the island of Maui, which is a practical range for helicopter support.

Base support

Land support facilities on Maui include docks, an airport, warehouse and housing facilities, and four daily commercial flights to and from Honolulu, and once-a-week freight barge service.

Labor supply

There is a plentiful local supply of semiskilled and skilled labor in Hawaii. Wages are the same as those prevailing on the mainland West Coast.

Cost of living

Living costs are somewhat higher than on the mainland because most staple food stocks and fuel have to be imported. Rents are also higher because of higher building material costs. However, these cost increases are offset in part by the fact that neither home heating nor air conditioning is required. The net increase in living costs over those on the mainland is within 5%, which is no greater than the difference noted between mainland cities, and less than between some cities.

Scientific cooperation

The Institute of Geophysics at the University of Hawaii at Honolulu has staff, equipment, a research vessel, shops, and an IBM 7040 and 1410 computer that can contribute to the success of the operation. The university also has an engineering school and departments in all the basic sciences, and graduate programs and staff in meteorology, geophysics, geochemistry, geology, astrophysics, oceanography, hydrology, and geodesy. The staff and facilities of the U.S. Geological Survey at the Hawaiian Volcano Observatory, as well as the U.S. Coast and Geodetic Survey Geophysic Observatory staff can also be called upon for cooperative assistance.

Other facilities

There are many facilities that can contribute directly or indirectly to the program. The U.S. Navy, for example, maintains a major shipyard and repair facility at Pearl Harbor. Honolulu is the primary mid-Pacific operations base for the U.S. Coast Guard. Emergency helicopter support is available from both the Coast Guard and the U.S. Marines. Honolulu is served by several steamship lines, and three scheduled airlines maintain service to the mainland with over 12 flights in each direction every day. Honolulu is a major manufacturers' distribution center, with parts and service facilities covering a broad spectrum of industrial equipment. There are commercial shipyards and shops, and one of the world's major heavy construction firms has its main office in Honolulu, as does the company that calibrates and maintains most of the Navy's electronic equipment.

Official support of local government

The state of Hawaii has a science-conscious Governor and Legislature, who can be counted on to provide not only moral support but also possibly some financial aid for support facilities and any legal assistance or legislative action required to facilitate the operation.

Scientific benefits to be obtained

The principal scientific advantages in drilling the Moho Hole in the Hawaiian area are briefly as follows:

1. The mean mantle velocity in the area north of Maui (8.27 ± .2 km/sec) is normal for the Pacific Ocean, and agrees closely with the mean of all measurements in the Pacific (8.25 km/sec). The mantle rock sampled, therefore, can be expected to be representative for the Pacific area as a whole.

2. The mantle material, on the basis of the seismic velocity measurements in the proposed site area, is truly anisotropic in that the spreads oriented north to south show a velocity of approximately 8.0 ± 0.1 km/sec, whereas those oriented east to west show a velocity of 8.55 ± .2 km/sec. Cores here, therefore, should permit the determination of the cause of anisotropic transmission and identify the minerals causing it.

3. The crustal structure at the NSF-recommended site shows not only a local thinning of the crust, but also a somewhat subnormal thickness of the basal crustal layer, which has a higher than normal velocity (6.96 km/sec) as compared to 6.84 km/sec for the area as a whole. In addition, the overlying intermediate crustal layer has a somewhat greater than normal thickness and lower than normal velocity of about 5.8 km/sec. It appears, therefore, that this thickening of the second crustal layer has been made at the expense of the underlying basal layer. There also may have been attrition of the basal layer from below, as evidenced by the rise in the crust-mantle interface. The alternate interpretation for the rise in the M discontinuity is that it is caused by domal uplift due to outward flow of mantle material from beneath the Hawaiian Ridge caused by crustal subsidence. The upper crustal layer having a velocity of about 4.2 km/sec is normal for the area with a thickness of about 1 km.

As the crustal structure is not strictly normal, one might argue that this is not the place to drill to the mantle. Conversely, one can also argue that it is the place to drill in that a significant physical-chemical process involving both the mantle and crust and two seismic discontinuities appears to be active and can be studied here. If Hess is right, and serpentinization of olivine-rich mantle rock determines the location of the Moho; and if the crust is really serpentinite, as Hess postulates, with a thin veneer of extruded basalt on top, here is an opportunity to study an area where serpentinization appears to be migrating as a wave front through the crust, with a following wave front of deserpentinization. Whatever the mechanism that will explain the observed structure, it appears to be of fundamental importance and one that might well have a bearing on the whole problem of the development of crustal structure, the thickness of the crust, the depth of the Moho, and how isostasy is maintained. A drill hole here, therefore, would provide auxiliary scientific information of considerable importance.

4. Auxiliary considerations are:

a. The U.S. Geological Survey and the University of Hawaii are conducting continuing and extensive petrological, geochemical, and geophysical studies in the present active volcano at Kilauea, which is drawing material from a depth of 40–45 km below the mantle-crust boundary. Thus, there will be a continuing scientific program related to the Moho Hole operation.

b. The Hawaiian primary lavas are tholeiitic and, because of their depth of origin, can be related directly to the composition of the underlying mantle. Knowing the chemical composition and mineralogy of the mantle, the process of differentiation leading to tholeiitic and alkalic basalts can be realistically studied.

c. The high velocity, high density pipe filling on Oahu, at a depth of less than 6000 ft, can be drilled at relatively low expense to determine the chemical and petrologic nature of recrystallized mantle material which appears to have undergone very little change in physical properties, but which may represent an important phase in the chain of transformations from mantle material to tholeiitic basalt.

d. The existing wealth of geophysical, geo-

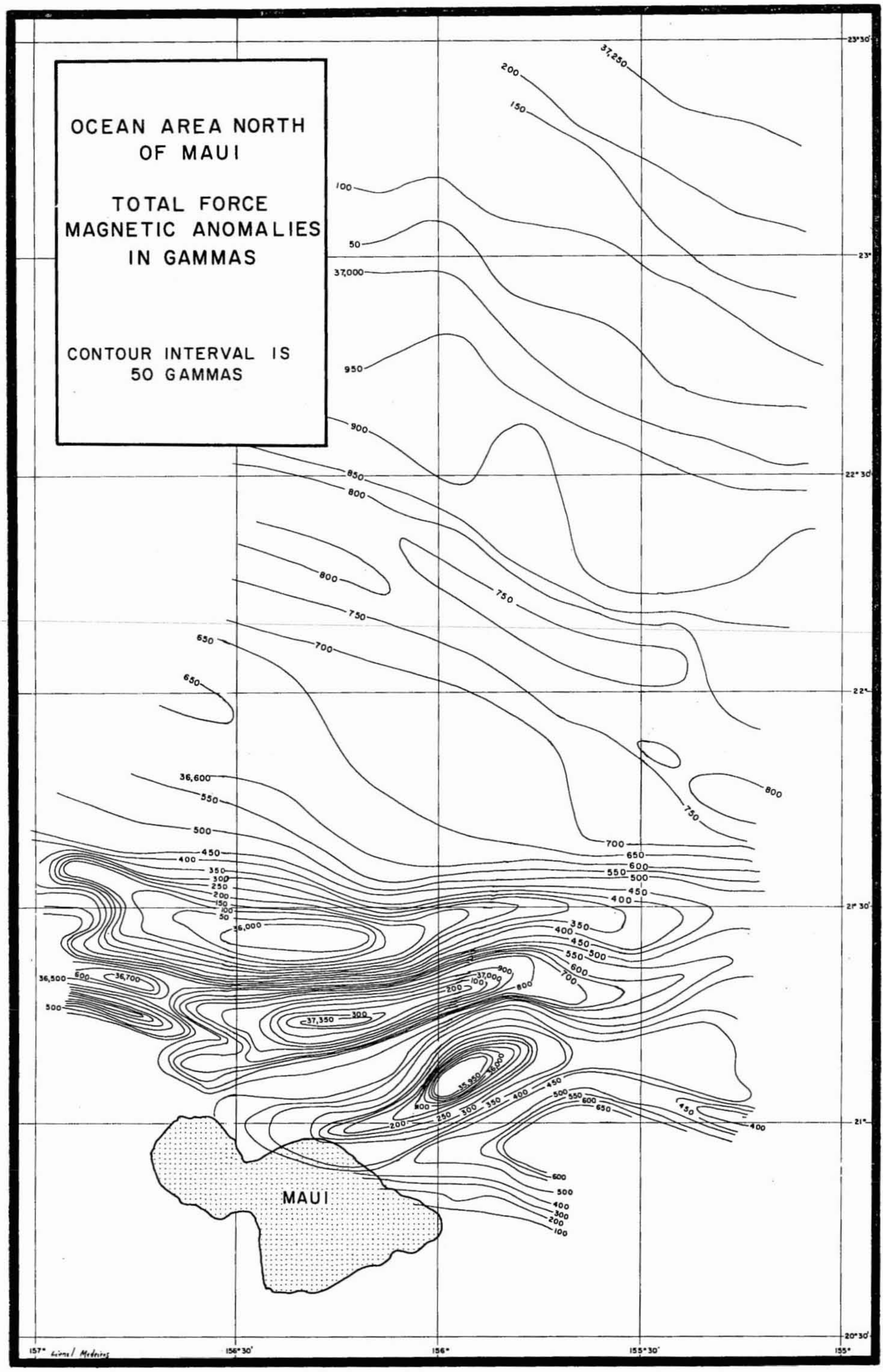

FIG. 2. Map of total force magnetic field north of Maui.

chemical, and geologic information in the Hawaiian area will permit a more intelligent analysis of the Moho Hole data than can be undertaken in almost any other area.

Summary

The arguments for locating the Moho Hole at Hawaii are all favorable from the practical viewpoint of bringing off a successful operation. This is extremely important from the standpoint of obtaining support for drilling other such holes elsewhere. Failure to drill to completion—because of some natural catastrophe, such as a hurricane; the incurrence of higher than anticipated costs because of logistic support problems over distances greater than that associated with the Hawaii site; delays caused by inferior local support—might well jeopardize future operations of this type. It is imperative, therefore, that the initial undertaking be made where possible adverse extraneous factors affecting the operation are minimized. Admittedly, the depth of drilling to the Moho off Hawaii is somewhat greater than that determined off Antigua, but a technology capable of drilling to 8 km should be capable of drilling to 9 km equally ~~as~~ well. The difference in dollar costs is not regarded as significant, because the additional drilling costs off Hawaii will be offset by savings in logistic and supply costs.

From a scientific standpoint, there is no question regarding the superiority of Hawaii as a site for the Moho Hole. There are no indications of faulting or other tectonic factors that might influence pressure and temperature relations, and hence, the character of the mantle. Although the structure of the crust at the recommended site is locally somewhat abnormal, this actually is a favorable circumstance in that drilling here would permit a second major scientific problem, the origin of the crust, to be investigated in an area where it is undergoing change. A third major scientific problem, the derivation of tholeiitic basalts, probably can be resolved by drilling off Hawaii. The drilling of a shallow hole to sample mantle-like material on Oahu would further add to the significance of the program and give valuable information on the chemical homogeneity of the mantle over a span of some 200 miles. Finally, the results can be integrated with those of related geological, geochemical, and geophysical research programs that have been operating in Hawaii for a number of years, and which will be maintained on a continuing and expanded basis, and thus contribute to the significance of the operation for many years to come.

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