BULLETIN OF THE EARTHQUAKE
RESEARCH INSTITUTE
Vol. 40, (1962), pp. 425-430

20. A Note on Crustal Structure.

By Keiiti AKI,

Earthquake Research Institute.

(Read March 27, 1962.—Received June 30, 1962.)

A remarkable correlation was found by Ewing and Press[1] between the phase velocity of Rayleigh waves and the Bouguer gravity anomaly throughout the United States. A similar correlation was found by Aki[2] for Japan. Fig. 1 shows the phase velocity of Rayleigh waves with

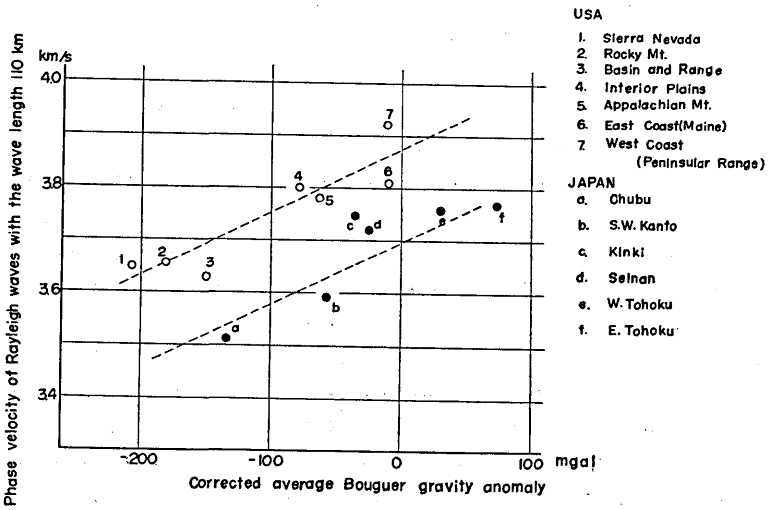

Fig. 1.

the wave length of 110 km in each region plotted against the Bouguer anomaly averaged over the region. The Bouguer anomaly value in Fig. 1 is that corrected for the variation in the crustal structure outside of the corresponding region, and each value may be regarded as representing the Bouguer anomaly for a horizontally uniform crustal structure having the same characteristics as the average structure within the region. In this correction, the variation in the crustal structure was approximately represented by the thickness variation of a single layer crust having the density contrast of 0.43 g/cc[3] to the mantle, and Hubbert's line integral method[4] was applied to a crustal cross-section assumed on the basis of the present knowledge available from the gravity[5),6),7),8)], phase velociiy[9),1),2)] and refraction studies[10),11)]. The value of correction is small for most of the regions, lying between -20 and $+20$ mgal, except in the Sierra Nevada region (-67 mgal), in the south western Kanto (-60 mgal) and in the Chubu region (-100 mgal). The choice of other possible models for the crustal variation will not seriously affect the corrected gravity values, and the values in Fig. 1 are probably correct within the error of ± 20 mgal. The experimental errors in the phase velocity determination are 0.03 to 0.05 km/sec for most of the regions.

It is clearly shown in Fig. 1 that 1) a roughly linear relation (with the coefficient of about 825 mgal per km/sec) exists between the phase velocity of Rayleigh waves and the corrected Bouguer anomaly within each of the two countries, 2) the points for the United States are significantly apart from those for Japan, and 3) the points for both countries align nearly parallel to each other. These are purely observational results except for the small correction on the Bouguer anomaly, and indicate that there is a significant difference in the material and/or the physical condition in the crust between both countries. Also, it is suggested that the variation in the crustal structure within each country may be governed by the same law. In the present note, the writer tries to find a quantitative difference in crustal material between both countries by interpreting Fig. 1 under the following two extreme assumptions regarding the crustal structure variation.

In one of the assumptions, the densities, wave velocities and thickness proportions of the layers constituting the crust are kept constant and the total crustal thickness is taken as the only variable. In the other, we assume that the layer thicknesses are constant everywhere and the density and elastic wave velocities vary from place to place. The former may be called Airy's assumption and the latter Pratt's assumption.

In discussing Fig. 1 under Airy's assumption, we shall adopt Press' standard continent as the model of the crust in the United States, and a modified one[2)] as that in Japan. In Press' model (case 6E)[12)], the phase velocity c of Rayleigh waves varies with the crustal thickness d at the rate of about -0.014 km/sec per km for the wave length of 110 km. The Bouguer anomaly variation ΔB corresponding to the crustal thickness variation Δd may be expressed as

$$\frac{\Delta B}{\Delta d} = -2\pi G \sum \Delta\rho_i \frac{d_i}{d} \, ,$$

where $\Delta\rho_i$ is the density difference between the ith layer and the mantle, d_i is the thickness of the ith layer, d is the total thickness and G is the gravitational constant. Press assigns density values to his layers according to Nafe and Drake's experimental curve which gives the density as a function of the compressional velocity. The average density contrast $\sum_i \Delta\rho_i(d_i/d)$ is 0.5 in Press' case 6E, and $\Delta B/\Delta d$ is obtained as -21 mgal per km. Dividing this by -0.014 km/sec per km, we have the result that $\Delta B/\Delta c$ should be about 1500 mgal per km/sec. The actual value of $\Delta B/\Delta c$ in Fig. 1 is about 825 mgal per km/sec and the discrepancy seems to be significant. The average density contrast which explains the observed value of $\Delta B/\Delta c$ is 0.28. Thus, if the mantle has the density of 3.32, the average crustal density must be as high as 3.04. This is essentially the same result obtained by Woollard[14], and he thinks that this high density is geologically unlikely. Also, Tsuboi found that the density contrast of 0.3 is most appropriate in determining the crustal thickness variation in California from gravity.

The crustal thickness corresponding to a given phase velocity for the wave length of 110 km can be obtained by the use of Press' standard curves[2] for the United States, and that for Japan by the use of Aki's modified standard curves[2] which give the thickness in agreement with the refraction result in Japan. Then, the difference in the position in Fig. 1 between a region in Japan having a given crustal thickness and a region in the United States having the same thickness must be attributed to the difference in density and velocities of the crustal material. The difference is about 0.2 km/sec in the phase velocity and about 20 mgal in the Bouguer anomaly. If the density difference is assumed to extend to the depth of 50 km, we have the result that the crustal density in Japan is smaller by about 0.01 g/cc than that in the United States. We also have the result that the shear velocity in Japan is lower by about 0.22 km/sec than that in the United States.

It is known from the experiments[15] on rocks at high pressure that the density may be expressed as a roughly linear function of the compressional velocity for a variety of rocks. The linear coefficient is about 1 g/cc per 3 km/sec. If this formula is applied to the shear velocity difference between the United States and Japan, the expected difference in density may be obtained as 0.12 g/cc on the assumption of Poisson's ratio 0.25. Since the density difference derived from Fig. 1 is 0.01, we may conclude that the difference in crustal density is negligible between the two countries despite the significant difference in shear velocity. This is the consequence of Airy's assumption. Now, let us see what will arise from Pratt's assumption.

Since, in Pratt's assumption, the crustal thickness is kept constant, the phase velocity of Rayleigh waves will be determined mostly by the shear velocity of crustal material. We may assume that the phase velocity varies linearly with the shear velocity at the rate of 0.92. Then, $\Delta B/\Delta c$ may be expressed in terms of $\Delta\rho/V_p$ of the crustal material as follows,

$$\frac{\Delta B}{\Delta c}=\frac{2\pi Gd}{0.92}\cdot\frac{\Delta\rho}{\Delta V_p}\cdot\frac{\Delta V_p}{\Delta V_s}$$

where d is the crustal thickness and V_p, V_s and ρ are the compressional velocity, shear velocity and density respectively. According to laboratory experiments[14], $\Delta\rho/\Delta V_p$ is about 1/3 g/cc per km/sec. Assuming the Poisson's ratio of 0.25, we have

$$\frac{\Delta B}{\Delta c}=22.3\times d \text{ (in km) mgal per km/sec.}$$

Comparing this with the observed value of 825 mgal per km/sec, we obtain the crustal thickness d of 37 km. This value is very reasonable as the average crustal thickness in the continent, and we see that Pratt's assumption explains the crustal variation, as well as or even better than Airy's, as far as the phase velocity-Bouguer anomaly diagram is concerned.

The crustal thickness of 37 km gives the density difference of 0.13 g/cc between the coast and the mountains (Sierra Nevada, Basin and Range, and Rocky Mts.) in the United States. Thus, if the average crustal density in the coast is 2.85[10], it is 2.72 in the mountains. The elevation in the mountains required for Isostasy is, then, computed as 1.7 km, which is not far from the average elevation of the regions concerned. On the other hand, the corresponding elevation computed under Airy's assumption (with the density contrast of 0.28 g/cc) is 1.4 km, which is a little smaller than the actual.

According to Birch[15], for variety of rocks at high pressure, the density may be expressed as a linear function of the compressional velocity with the mean atomic weight as a parameter. The value of $\Delta\rho/\Delta V_p$ which we adopted in computing $\Delta B/\Delta c$ is nearly equal to that for a constant mean atomic weight. Therefore, if the crustal velocity and density for various regions derived under Pratt's assumption are plotted on Birch's diagrams, the points will align parallel to the line for a constant mean atomic weight. The points for Japan and those for the United States, however, will not lie on the same line, but on separate lines with different mean atomic weight. The difference in the mean atomic weight may be evaluated as follows.

As shown in Fig. 1, the difference in phase velocity between a region in Japan and one in the United States with the same gravity anomaly is about 0.18 km/sec. Since the same gravity anomaly means the same crustal density under Pratt's assumption, this difference may be regarded as the difference between the crustal material with common density. The compressional velocity difference corresponding to the above phase velocity difference may be about 0.35 km/sec. Birch's diagram shows that the mean atomic weight changes with the compressional velocity at the rate of -1 per 0.8 km/sec if the density is kept constant. Thus, we have the result that the mean atomic weight of the crustal material in Japan is greater by about 0.4 than that in the United States. This suggests that the crustal rocks in Japan may be relatively rich in minerals with heavier elements. Prof. H. Kuno mentioned that there is some evidence of relatively high concentration of Fe in the rocks in Japan. Geological evidence, however, seems not to give a definite statement on the compositional difference between Japan and the United States.

The differences in crustal velocities and density between both countries derived under Airy's assumption may also be attributed to nearly the same difference in the mean atomic weight. However, since the mean atomic weight may not be the only factor which determines the velocity-density relation, we cannot exclude other possibilities which may explain the observation. For instance, the presence of magma patches in the crust in Japan might account for the low velocity crust with a very slightly reduced density.

References

1) M. EWING and F. PRESS, *Bull. Geol. Soc. Am.*, **70** (1959), 229-244.
2) K. AKI, *Bull. Earthq. Res. Inst.*, **39** (1961), 255-283.
3) J. L. WORZEL and G. L. SHURBET, *Geol. Soc. Am. Spec. Pap.* **62** (1955), 87-100.
4) M. K. HUBBERT, *Geophysics*, **13** (1948), 215-225.
5) G. P. WOOLLARD, *Bull. Geol. Soc. Am.*, **54** (1943), 747-790.
6) C. TSUBOI, T. KANEKO, S. MIYAMURA and T. YABASI, *Bull. Earthq. Res. Inst.*, **17** (1939), 386-410.
7) S. YAMAGUTI, *Bull. Earthq. Res. Inst.*, **17** (1939), 429-442.

8) C. TSUBOI, *Bull. Geol. Soc. Am.*, **67** (1956), 1641-1646.
9) F. PRESS, *Bull. Geol. Soc. Am.*, **67** (1956), 1647-1658.
10) C. L. DRAKE, M. EWING and G. H. SUTTON, Physics and Chemistry of the Earth V3, Pergamon Press, London, 110-198.
11) T. MATUZAWA, *Bull. Earthq. Res. Inst.*, **37** (1959), 123-154.
12) F. PRESS, *J. Geophys. Res.*, **65** (1960), 1039-1051.
13) J. E. NAFE and C. L. DRAKE, (unpublished), See, e. g., M. TALWANI, J. L. WORZEL and M. EWING, *J. Geophys. Res.*, **66** (1961), 1265-1278.
14) G. P. WOOLLARD, *J. Geophys. Res.*, **64** (1959), 1521-1544.
15) F. BIRCH, *J. Geophys. Res.*, **66** (1961), 2199-2224.

20. 地殻構造に関する一考案

地震研究所 安 芸 敬 一

波長 110 km のレーリー波の位相速度を，日本および米国の各地域について求めて，それと各地域のブーゲー異常との関係をみると，図 1 のようになる．著しいことは，日本と米国の点がはつきり 2 つにわかれること，両国内での変化のありさまは，大体並行であることである．但し，上のブーゲー異常は，簡単な仮定のもとに，水平方向の不一様について補正してある．この小論では，以上の関係をプラットおよびエアリーの仮定のもとに，定量的に議論した．日本の地殻を構成する物質は，米国のそれと比べて弾性波速度が 5% 位小さいが，それにも拘わらず密度は殆んど異ならない．これは，日本の地殻に，マグマのパッチや，弱線，断層などが複雑に入りこんでいるためかもしれない．また，化学組成のちがいによるとすれば，そのちがい方は，日本の地殻の平均原子量は米国のそれより，0.4 だけ大きいということになる．