Thickness of the Earth's Crust in Antarctica and the Surrounding Oceans : A Reply

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Summary

The paper of Evison, Ingham, Orr & Le Fort on the dispersion of earthquake waves traversing Antarctica has recently been criticized by Bentley & Ostenso and by Kovach & Press. The discovery that the crust of eastern Antarctica is of continental thickness whilst that of Marie Byrd Land is some 10 km thinner is accepted by these critics, but they object to the two-layer and three-layer models used in obtaining this result, and also to the values that were assigned to the velocity parameters. For detecting large differences in crustal thickness, however, the traditional simple models have not been invalidated by the advent of the digital computer, which comes into its own with subtler problems; but the velocities appropriate to a simple model are not necessarily those indicated by refracted waves. Kovach & Press also criticize the use of Love waves rather than Rayleigh waves for investigating the oceanic crust around Antarctica. Their arguments on this point carry the unsatisfactory implications that the average velocity in the oceanic crust ought to increase with the thickness, and that there should be gross regional departures from isostasy at sea.

1. Introduction

Dispersive waves from eight earthquakes at Hallett Station, Scott Base and Mirny Station were used by Evison, Ingham, Orr & Le Fort (1960) to show that the crust of eastern Antarctica is of continental thickness whilst that of Marie Byrd Land is about 10 km thinner. Recent papers by Bentley & Ostenso (1962) and Kovach & Press (1961b) have subscribed to this result, although preferring to take the thickness of the typical continental crust as 40 km instead of 35 km. At the same time, these authors have criticized the theoretical crust-mantle models by means of which the result was obtained, and also the values that were assigned to the velocity parameters.

The original paper also showed from Love wave dispersion that the thickness of the solid crust in the oceanic regions surrounding Antarctica varies from about 5 km to about 10 km, the smaller values being associated with the deeper basins. It was demonstrated that oceanic Rayleigh waves do not provide a reliable measure of the thickness of the crust, let alone the thickness of bottom sediments. These results have now been criticized by Kovach & Press (1961b, c).

Several questions of importance to the dispersion method arise out of these criticisms. Have dispersion studies based on simple two-layer or three-layer models become invalid now that many-layered models can be analysed by digital computer? How relevant to dispersion models are the values of seismic velocity indicated by refracted waves? What is involved in comparing thicknesses determined by the dispersion method and by other means? What is the inherent power of the method to reveal the layering of the crust and upper mantle? These questions will be briefly touched on in the present reply.

2. Choice of model

The simplest model that can be used to estimate the thickness of the crust, from observations of dispersive waves, represents the solid crust by a uniform layer and the mantle by a uniform half-space. For Rayleigh waves traversing the ocean the water layer must be added. Computations for these models can reasonably be undertaken on a desk calculator. Up to the date of the paper under discussion, nearly all dispersion studies that had appeared in the literature were based on these models, and they are still being extensively used. Nevertheless, Bentley & Ostenso (1962) and Kovach & Press (1961b) reject these models as "oversimplified".

In any theoretical model set up for the purpose of interpreting observational data the degree of elaboration that is appropriate depends on how much detail the results are required to show, and this cannot be pushed beyond what the observations will bear. The object of the original paper was to find whether eastern and western Antarctica are continental. In the outcome, the eastern Antarctic crust was shown to have an average thickness of about 35 km, which is the characteristic value for continents *on the adopted model.* Marie Byrd Land, on the other hand, turned out to have a crustal thickness of 25 km, or 10 km less than the continental value, and this led to the conclusion that Marie Byrd Land is not truly continental.

Reinterpreting some of the same data in terms of a relatively complicated model, with the help of the digital computer, Kovach & Press (1961b) have deduced that the eastern Antarctic crust has an average thickness of about 40 km, which is the characteristic value for continents *on their model.* In Marie Byrd Land they have found a thickness of 30 km, again 10 km less than the continental value.

This illustrates what has always been known, that the precise value of crustal thickness given by the dispersion method depends partly on the theoretical assumptions. Kovach & Press estimate that the accuracy of their 40 km value is not better than $\pm$ 12 per cent, and since the method purports only to give an average thickness over long distances there would be little point in striving after a more precise value. But the simple model was just as effective as the elaborate one in revealing the essential difference between eastern Antarctica and Marie Byrd Land. Indeed, Kovach & Press (1961b) reached much the same conclusion as the original paper, stating that there is "a normal crust in East Antarctica and a thinner crust in West Antarctica". Bentley & Ostenso (1962), from a study of gravity and surface elevation, deduced the same crustal thicknesses as did Kovach & Press, and they have claimed that in the original paper, too, these values could have been obtained by a more suitable choice of parameters. But they unaccountably conclude that "West Antarctica appears to be truly continental in structure".

The dispersion method relies on an observed variation of velocity with period which is usually quite uncomplicated. For this reason, the significance of the finer details in an elaborate interpretation may often be illusory. Furthermore, the goodness of fit achieved by Kovach & Press (1961b) in their reinterpretations of data taken from the original paper was sometimes better and sometimes worse than was achieved with the simple model, but not markedly different on the whole.

Thus the simple model and desk calculator are adequate for such a task as showing whether a given region is continental or not. Recent studies in the New Zealand area, with the same theoretical assumptions as were adopted for Antarctica, have shown that New Zealand itself is continental (Thomson & Evison, 1962), but that the adjacent submerged region of the Campbell Plateau has a crust of little more than half the continental thickness (Adams 1962).

3. Choice of parameters

In representing the crust and mantle by some chosen model the most suitable values to assign to the parameters at a particular depth will depend to some extent on the complexity of the model. A section of the original paper was devoted to a discussion of the proper choice of parameters for the simple models used. From the numerous dispersion graphs included in that paper it may be seen that the chosen values led to a better fit between observation and theory than has often been attained. Nevertheless, Bentley & Ostenso (1962) and Kovach & Press (1961b) reject the values in favour of more "realistic" ones.

The shear velocity in the mantle plays an important part in the dispersion of Love and Rayleigh waves, and the value 4·50 km/s that was assigned to this parameter is one of those criticized. Kovach & Press (1961b) state that this value is "outmoded". In their reinterpretation of some of the original data, using a many-layered model, they are able to include in the mantle a low velocity zone having a total thickness of 200 km; this results in an improved fit at the longer periods. They also adopt three different sets of parameters: one for continents, a second for the Indian Ocean, and a third for other oceans. The thicknesses (H) and shear velocities (β) which they ascribe to the various mantle layers are shown in Table 1.

Table 1

Mantle layering (Kovach & Press 1961b)

Continent		Indian Ocean		Other Oceans	
H(km)	β(km/s)	H(km)	β(km/s)	H(km)	β(km/s)
13	4·60	39	4·50	39	4·60
25	4·50	25	4·49	25	4·49
50	4·41	50	4·30	50	4·38
75	4·41	75	4·30	75	4·38
50	4·50	50	4·44	50	4·44
∞	4·60	∞	4·60	∞	4·60

Let us accept these various sets of shear velocities as a basis for choosing a single value to assign to the mantle (regarded as a uniform half-space) in a hitherto uninvestigated region. Considering that the most effective part of the mantle, for the waves in question, is the top 100 km or so, one would evidently choose a value not much different from 4·50 km/s.

According to Bentley & Ostenso, however, the shear velocity in the mantle should have been assigned the much higher value 4·70 km/s. They take the view that "velocities which agree with refraction results can be used to advantage in dispersion analyses". This predilection for refraction values is misplaced, as can be demonstrated more effectively now than when the original paper was written; though it was there mentioned (p. 295) that "refracted waves are apt to indicate the velocity near the upper surface of the refracting layer", and that values obtained by such means "cannot well be adopted for theoretical purposes until more complex models can be readily analysed".

This point has now been nicely illustrated by means of the digital computer. In another paper, Kovach & Press (1961a) have given an alternative mantle model for the Indian and Eastern Pacific Oceans, with layers having the thicknesses and shear velocities shown in Table 2.

Table 2

Mantle layering, Indian and Eastern Pacific Oceans
(Kovach & Press 1961a)

H(km)	β(km/s)
3	4·73
33	4·50
173	4·30
100	4·60
etc.	

This model was devised specifically to give the upper mantle an effective shear velocity close to 4·50 km/s, as required by dispersion data, and at the same time to accommodate the much higher value (4·73 km/s) indicated by refracted waves. Kovach & Press (1961b, p. 219, footnote) state that the two Indian Ocean models detailed in Tables 1 and 2 above give "almost identical dispersion values". This is to say that the refraction velocity has a neglible effect on dispersive waves and may be safely ignored in a simple model. To see whether the refraction velocity might not be given greater prominence, Kovach & Press (1961a) have actually computed models in which the mantle is regarded as a half-space; they tried the shear velocities 4·73 km/s and 4·68 km/s, but found them both much too high. Thus the proposal of Bentley & Ostenso has been refuted by Kovach & Press.

The choice of a value for the shear velocity in the crust may be discussed along much the same lines. Here again the value adopted in the original paper (3·47 km/s) has been criticized as unrealistic because the refraction method has indicated higher values. But the adopted value gave in general a very good fit between theory and observation. Moreover, in the reinterpretations given by Kovach & Press (1961b), the fit at the shorter periods would on the whole be improved by reducing their values of crustal shear velocity. The digital computer might be used to show how the velocities indicated by refracted waves could best be accommodated in the crust, as has been done for the mantle.

4. Thickness of crust in Marie Byrd Land

The values of crustal thickness derived in the original paper evidently cannot be modified by the means suggested by Bentley & Ostenso, and it is therefore desirable to examine the alleged discrepancy between the thickness for Marie Byrd Land (25 km) and the corresponding value which they have put forward (30 km) from observations of gravity and surface elevation.

The evidence presented by Bentley & Ostenso does not actually establish any such discrepancy, for the two regions studied are not the same. This is not fully apparent from their paper because the maps presented, although purporting to to show the region covered by the original dispersion study, do not show it all. In that study, as was shown in Figure 1 of the original paper, four wave-paths across Marie Byrd Land were analysed, and each indicated an average crustal thickness of about 25 km. One of these paths was completely outside the area studied by Bentley & Ostenso, and the proportions of the other paths lying outside their area were about 60 per cent, 60 per cent, and 40 per cent, respectively. In the main, these portions lay close to the coastline or out on the shelf, where a slightly thinner crust might be expected. Adding to this that Bentley & Ostenso give an estimated standard error of 4 km for their values of thickness, one may conclude that there is no discrepancy to account for.

The contrast between Marie Byrd Land and eastern Antarctica, which was the chief outcome of the dispersion study, was established by comparing the four wave-paths mentioned above with six eastern Antarctic wave-paths. Bentley & Ostenso contribute a solitary gravity determination for eastern Antarctica, giving a thickness of 36 km in Victoria Land. They also cite a value of 40 km at Komsomolskaya, based on an assumed 33 km at Mirny. With this evidence, they maintain that "although scarcity of data prevents a definite conclusion, it can at least be said that an average crustal thickness of 40 km in East Antarctica is reasonable". The dispersion results for eastern Antarctica gave about 35 km for all six wave-paths, which were widely distributed and traversed a total distance of over 18 000 km. A thickness of 35 km would thus seem to be more reasonable.

But the values of crustal thickness in Antarctica obtained by Bentley & Ostenso from gravity and elevation surveys do not provide a critical test as between the thicknesses indicated by the original study and those preferred by Kovach & Press. It is of course enormously more difficult to find the average thickness over a large area by the methods used by Bentley & Ostenso than by observing the dispersion of earthquake waves; this is especially so for Antarctica, in spite of the lack of earthquake activity in the region. Observations of gravity and elevation are convenient means of investigating local variations of crustal thickness. The dispersion method, using group velocities, is unequalled for revealing the general character of regions as large as Marie Byrd Land or larger.

5. Thickness of oceanic crust

The dispersion method has been widely invoked as a means of finding the thickness of the crust in oceanic areas, especially by the use of Rayleigh waves (e.g. Press & Ewing 1955). It was demonstrated in the original paper, however, that values obtained from Rayleigh waves are unreliable; and the determinations given for oceanic areas around Antarctica were therefore based mainly on Love waves. Kovach & Press (1961b) now claim that oceanic Love waves are also unsatisfactory, first because periods up to about 22 s are strongly influenced by unconsolidated bottom sediments, about which little is known, and secondly because at periods above 22 s the group velocity is almost independent of crustal thickness. No evidence is presented for the statement about the shorter periods; it would be valuable to have this point clarified with the help of the digital computer.

To illustrate their stricture on oceanic Love waves of longer period, Kovach & Press (1961b, Figures 3 and 4) compare the dispersion curves for two model crusts, of thickness 5·5 km and 10·5 km respectively, and layered as shown in Table 3.

Table 3

Crustal layering, oceanic Love waves
(*Kovach & Press* 1961*b*)

H(km)	β(km/s)
0·5	0·50
2·0	2·93
3·0 or 8·0	3·90

These crusts they combine by turns with the two oceanic mantles given in Table 1. For each mantle the 5·5 km crust is found to be almost indistinguishable from the 10·5 km crust at periods above about 22 s. An objection to this argument is that the thickening was assumed to occur entirely in the high-velocity crustal layer, so that in effect the thicker crust was given an average velocity substantially higher than the thinner crust. This velocity increase, for which no justification was offered, has made the curves for the thin and thick crusts more nearly alike than they would have been if the average crustal velocity had been held constant. The effect of a thicker crust was thus obscured by introducing at the same time an arbitrary *increase* of crustal velocity.

A similar confusing element appeared in early attempts to allow for differing ratios of water depth to crustal thickness in the analysis of oceanic Rayleigh waves. It is remarkable that what was then assumed was a large *decrease* of crustal velocity with increasing thickness. Thus Press & Ewing (1955), using theoretical computations by Officer (1955), adopted a shear velocity of 3·98 km/s for a crust 5·57 km thick and 3·18 km/s for a crust 11·14 km thick. The unsatisfactory implications of this arbitrary change of velocity were pointed out by Evison, Ingham, Orr & Le Fort (1960), who mentioned that, on such evidence as can be obtained from refraction results (Hill 1957), the average velocity in the oceanic crust appears to be very nearly the same for a thickness of 10 km as for 5 km.

An outstanding advantage of the digital computer is that for any crust-mantle model it is easy to study the effect of varying, one or more at a time, the multiplicity of parameters that are involved. Once the programme has been written, there is little extra labour in computing for a variety of parameter values. It is entirely to be expected that when the thickness of a many-layered crust is varied, without altering the average velocity, Love waves will be found capable of distinguishing between thicknesses of 5 km and 10 km, just as with the simple model.

A useful restraint is placed on models for oceanic regions by the need to preserve isostasy, especially when one is considering average conditions over the distances used in the group velocity method. This point was mentioned briefly in the original paper in discussing the result, deduced from Love waves traversing the oceans around Antarctica, that the crust is thicker where the water is shallower. Isostasy is ignored in the critical remarks of Kovach & Press (1961c). Their Figure 1 shows a family of dispersion curves for oceanic Rayleigh waves, obtained by varying the thickness of the main crustal layer from 3·3 km to 10 km. All the other layers in the model are kept constant, including the water. The variation is thus tantamount to replacing 6·7 km of the deepest mantle layer, which was assumed infinitely thick and given density 3·49 g/cm^3, by 6·7 km of crustal rock with density 3·00 g/cm^3. This would involve a change of gravity by 137 mgal, and is therefore quite unacceptable.

6. Thickness of ocean sediments

Nothing in the critical remarks of Kovach & Press (1961c) seems to dispose of the view that the dispersion of Rayleigh waves has been mistakenly promoted as a means of measuring the thickness of unconsolidated ocean sediments. These authors state that the observed data should be in the velocity range 1·5–3·0 km/s. This limitation has not been complied with in the literature. For instance, five out of ten determinations recently published by Kovach & Press (1961a, Figure 5) for the Eastern Pacific appear to include no data for velocities below 3·0 km/s. Here Kovach & Press have themselves used a three-layer model, which they describe as "adequate to explain the data". By arbitrarily assigning the same value to crustal thickness and water depth, and varying this value from 4 km to 5 km, they again imply a gross change in gravity. The thickness of bottom sediments is supposedly determined by subtracting the bathymetric water depth from the depth inferred by means of dispersion, but this latter quantity is so affected by the arbitrary assumption just mentioned that neither the values of sediment thickness nor their variation can be taken seriously.

As mentioned above, Kovach & Press (1961b) criticize the use of oceanic Love waves of period less than 22 s, on the argument that these waves are very strongly influenced by the shear velocity in the bottom sediments, which is not well known. On the other hand they appear to insist (1961c) that Rayleigh waves of similar period can show whether these same sediments are nearer 0·5 km or 1·0 km thick. These propositions seem to be contradictory; it is difficult to see how both could be true.

7. Conclusion

Simple models, of the kind used by Evison, Ingham, Orr & Le Fort, following earlier authors, will continue to play an important part in dispersion studies. They illustrate the dominant features of the dispersion phenomenon. They also provide a useful check on results derived from the digital computer, the direct verification of which becomes more difficult in proportion as the model increases in complexity.

The inherent resolving power of the dispersion method is not high. The method gives a more or less generalized picture of the structure and elastic properties of the crust and outer mantle; the wavelengths are such that one cannot expect to discern fine details in the variation of elastic properties with depth. The group velocity method gives an average indication for the whole path, and only the grosser variations along the path can be separated out. Elastic properties indicated by body waves may pertain to such limited parts of the medium that they have little significance for dispersive waves.

An equally good fit to observed dispersion data may well be given by various theoretical interpretations, leading to somewhat different values of, say, the thickness of the crust. As with other geophysical methods, calibration is needed before absolute values can be accurately assigned; and the ultimate gauge is the drill-hole. It seems unlikely that the average thickness of the typical continental crust, for example, will become precisely known in the near future. Substantial variations of crustal thickness can be discovered, however, by several different means, and amongst these the dispersion of the group velocity of earthquake waves is the most effective for comparing regions of continental or sub-continental extent.

In the past the dispersion method has been hampered by the great labour that it takes to carry out the necessary computations by desk calculator. The disability has now been removed by the digital computer, which has so far been used mainly to raise the postulated number of layers in the crust-mantle model to nine or ten and sometimes more. Considering the simple nature of most graphs of observed dispersion, this multiplication of layers is perhaps of less value than would be a step-by-step variation of parameters in the two-layer and three-layer models.

The actual layering of the crust and mantle is presumably both complicated and variable, and where a degree of complexity is manifested by the dispersion data this can be exploited only by means of the digital computer. The computer has also proved useful for resolving an apparent conflict between the values of mantle velocity indicated by dispersive and refracted waves respectively. On the other hand it would assist the broad comparison of different geographical regions if new dispersion data were interpreted, as a matter of course, in terms of simple models with standard parameters; for these models are as valid as ever they were for disclosing substantial differences of crustal thickness, such as that between regions of shallow and deep ocean, or that between eastern Antarctica and Marie Byrd Land.

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