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RECENT EVIDENCE CONCERNING THE STRUCTURE OF THE UPPER MANTLE FROM THE DISPERSION OF LONG-PERIOD SURFACE WAVES[1]

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Most of our present detailed knowledge concerning the earth's deep interior has come to us from the study of body-wave travel-time data, supplemented by the semi-empirical use of amplitude information. The use of travel-time information alone, even in areas where it can be applied, has severe limitations. Velocity reversals lead to fundamental theoretical difficulties, and discontinuities in velocity or velocity gradient lead to formidable practical difficulties. However, it is just these features of the earth that are most interesting and important in discussions of earth history, mantle composition, phase changes, and convection. The long debate over the low-velocity zone and the so-called 20^o discontinuity illustrates the nature of the difficulties.

Surface waves and free vibrations of the earth offer an alternative method for exploring the earth's interior, in particular for the present discussion, the mantle. Until very recently formidable computational difficulties and instrumental limitations have prevented surface waves from being equally considered with body waves in detailed study of the mantle. The names of Benioff, Press, Ewing, and Gilman are associated with the removal of the latter limitation. Press, Ewing, Sato, and Aki are associated with various techniques for obtaining useful information from the long-period records. The development and refinement of methods for theoretical and numerical interpretation of the resulting data in terms of earth structure is associated with the names of Pekeris, Haskell, Dorman, Oliver, Ewing, Press, Takeuchi, Kobahashi, Gilbert, and MacDonald, who built on the broad base earlier laid out by Lamb, Love, Rayleigh, Jeans, Jeffreys, and Stoneley.

Gutenberg supplied some of the earliest surface-wave dispersion data. The method has since been used for the systematic estimation of crustal thickness in many parts of the world, but complete interpretation of surface-wave data to yield crustal and mantle structure has lagged far behind its collection because of the complexity of the numerical calculations involved. In fact, it was necessary to wait for the development and general availability of high-

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[1]Contribution No. 1219, Division of the Geological Sciences, California Institute of Technology. This research was partially supported by the Air Force Office of Scientific Research, Contract AF-AFOSR-25-63, as part of the Advanced Research Projects Agency, Project VELA.

speed digital computers before the work could begin. The theory for flat, homogeneous, isotropic layers was available by 1950, but did not lead to detailed numerical calculations until some ten years later. Moreover, it early became evident that the theory for flat, lying layers was insufficient for the interpretation of mantle surface waves. The complete problem formulated in terms of standing waves on a heterogeneous, gravitating, spherical earth is now well in hand theoretically. By straightforward means the free oscillation solutions may be used to calculate the dispersion relations pertinent to the interpretation of surface waves. Complete solutions have been obtained for the standard earth models of Jeffreys, Gutenberg, Bullen, Bullard, and Lehmann. However, even on a high-speed digital computer the calculations are so formidable that only the most tentative efforts have been made to modify the standard velocity structures to give a more satisfactory fit to dispersion data without violating the body-wave information.

As far as the mantle is concerned the potentiality of the surface-wave method has not yet been fully utilized. Mantle waves have served primarily as a check on certain proposed body-wave solutions and their worldwide validity. Recent research has shown that surface waves, properly used, are surprisingly sensitive to details of mantle structure. When these are used in conjunction with body-wave travel-time and amplitude data it is possible to considerably reduce the ambiguity that is present if the methods are used independently. The following criteria must be satisfied for an interpretation of the outermost 800 km of earth by means of surface waves:

(1) Existence of dispersion or free oscillation data in the period range 10 to 1000 seconds, accurate to at least 0.5% for both the Rayleigh and Love modes over a common, fairly uniform path. Any less accuracy makes it impossible to distinguish between the various models proposed from body-wave studies.

(2) An inversion method which makes it possible to place bounds on the possible structures that satisfy the dispersion, free oscillation, and travel-time data. The number of parameters involved in a realistic earth model is too great for standard trial-and-error techniques of matching theory to data.

(3) A method of rapidly computing dispersion over an arbitrarily heterogeneous, gravitating, spherical body.

These criteria are satisfied in the present study.

The findings of the study are as follows:

(1) The low-velocity zone is a widespread phenomena although it may be locally absent.

(2) The velocity starts to decrease at a depth of about 20 km below the base of the crust.

(3) The low-velocity zone, at least under oceans, extends to a deeper depth than previously supposed, to some 350 to 400 km. The velocity in the low-velocity zone is essentially constant although it seems to increase abruptly by 3% at about 150 km. The shear velocity in the low-velocity zone is between 4.35 and 4.55 km/sec.

(4) There is an extremely rapid increase in velocity between some 350 and 500 km depth, a much greater increase than that proposed by Jeffreys to explain the "20° discontinuity."

(5) The low-velocity zone is also a zone of high attenuation for seismic waves; the attenuation of shear waves in the low-velocity zone is an order of magnitude greater than that in the lower mantle.

(6) The theoretical travel times of shear waves for the preferred model exhibit a shadow zone which ends at 15°, a minor travel-time discontinuity at 18°, and a more pronounced travel-time discontinuity at 26.4°.

(7) The structure which satisifes Love-wave data gives theoretical Rayleigh-wave dispersion which is 0.03 to 0.04 km/sec above the data. This discrepancy can be removed by postulating a 10% anisotropy in the low-velocity zone.

Figures 4.1 and 4.2 summarize the situation as known up to about two years ago. Mixed path Love- and Rayleigh-wave data are plotted for comparison with the theoretical predictions for several of the standard velocity-density continental earth structures. The theoretical calculations, carried out by Bolt and Dorman [1], Takeuchi et al. [2], Alterman et al. [3], Kovach and Anderson [4], and Anderson [5, 6], are for spherical earth models. Although none of the data is for a purely continental path and good agreement cannot be expected, the Gutenberg velocity structure and the Bullen A density structure survive this first test. Since the effect of an oceanic crust would be to increase the theoretical phase velocities and most of the data is already below the theoretical curves, we could speculate at this point that the average shear velocity of the upper mantle is less than that given by any standard model.

Further progress had to await the development of convenient interpretation techniques. Dorman and Ewing [7] reported one approach to this problem. The methods used here were reported by Anderson [5, 6] and Archambeau and Anderson [8], and are based on a combined use of Rayleigh's principle and Haskell's method. Figure 4.3 gives the flow of the interpretation scheme. Figure 4.4 gives an example of the inversion parameters which are calculated analytically by a modification of Jeffreys' method [9]. Figure 4.5 gives the inversion parameters for the second Love mode, the so-called Sa wave. Of particular interest here is the suggestion that in the period range of about 15 to 20 seconds this mode "sees" the upper mantle from about 80 to 150 km more than it "sees" the crustal layer; this makes it a particularly important phase in the study of the upper mantle.

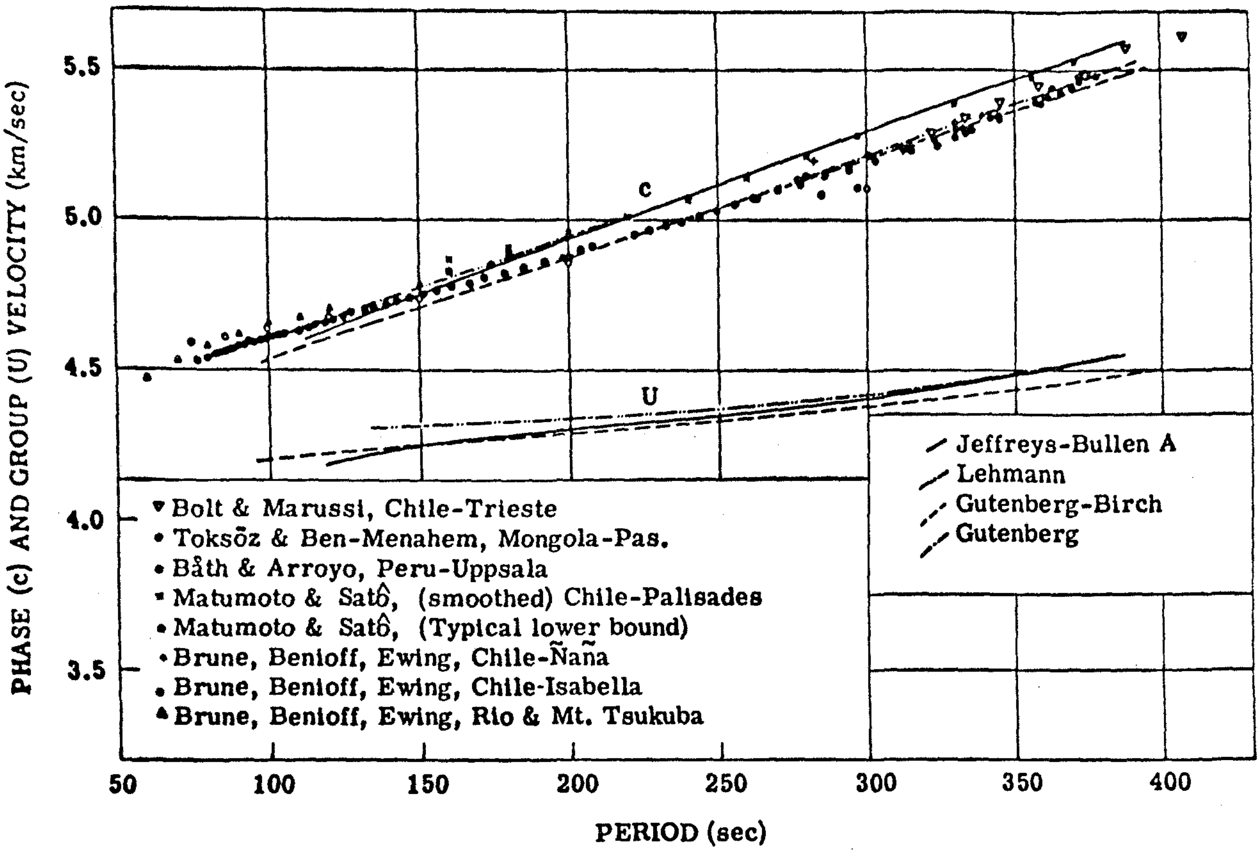


FIGURE 4.1. MIXED PATH LOVE-WAVE DISPERSION AND TORSIONAL OSCILLATION DATA COMPARED WITH THEORETICAL PREDICTIONS OF 4 CONTINENTAL EARTH MODELS

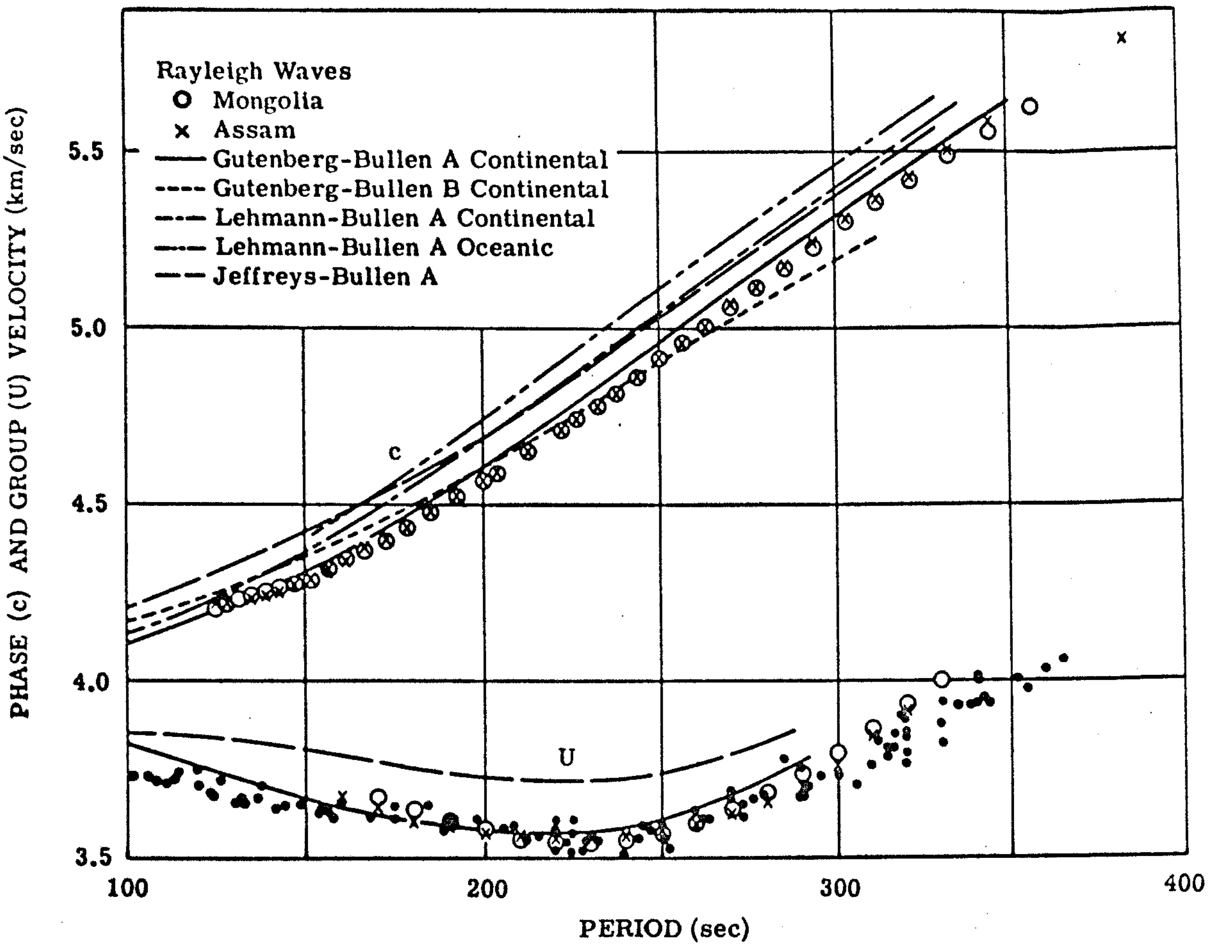


FIGURE 4.2. MIXED PATH RAYLEIGH-WAVE DATA [12] COMPARED WITH THRORETICAL PREDICTIONS OF FIVE STANDARD EARTH MODELS

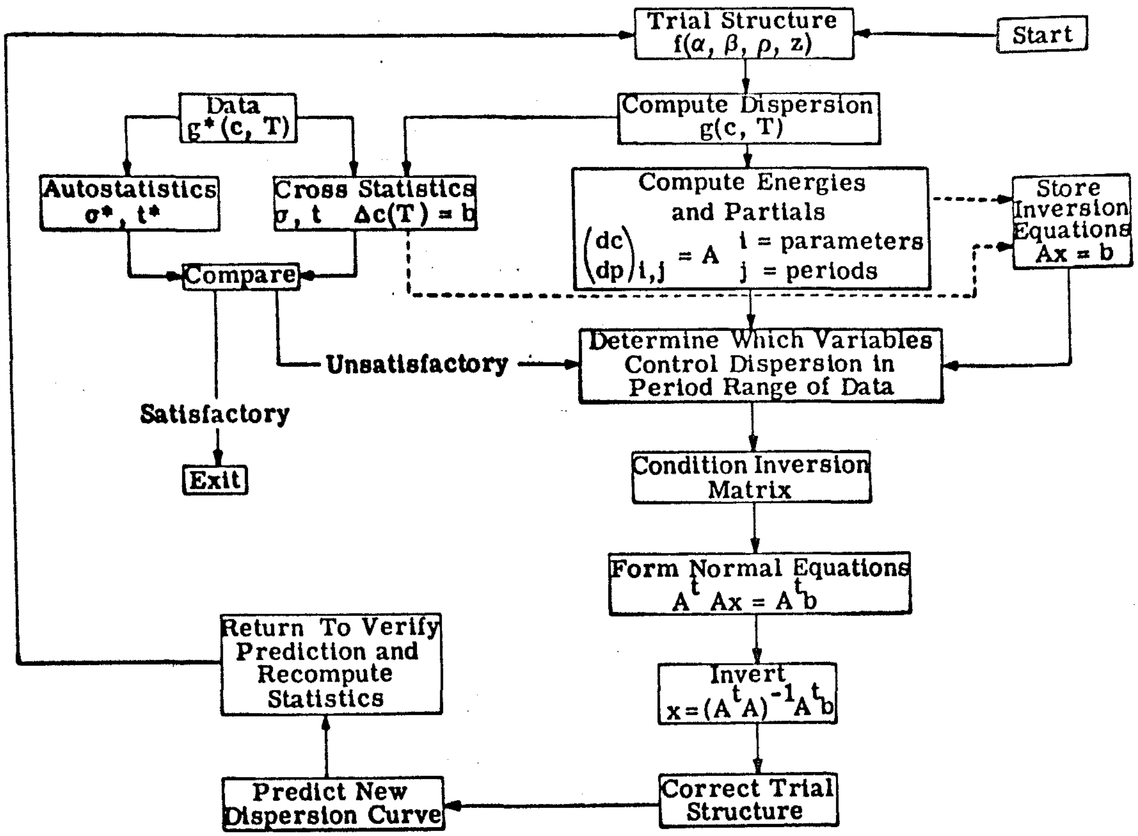


FIGURE 4.3. FLOW CHART FOR COMPUTER INTERPRETATION OF DISPERSION DATA

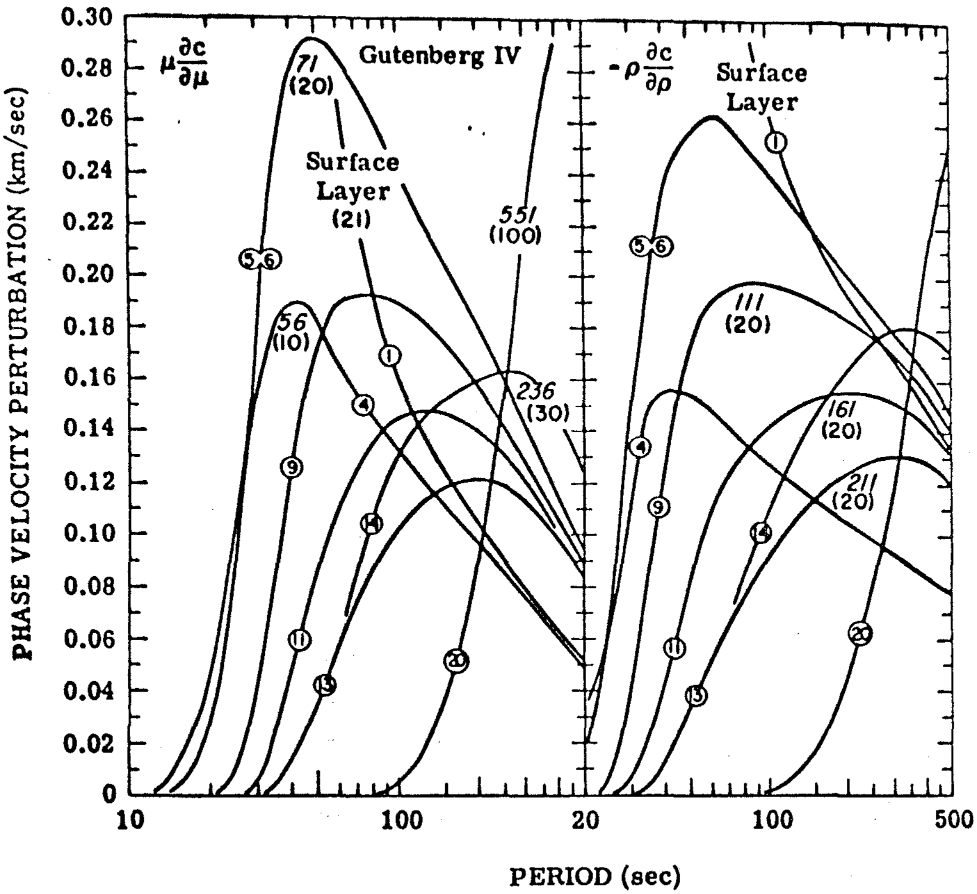
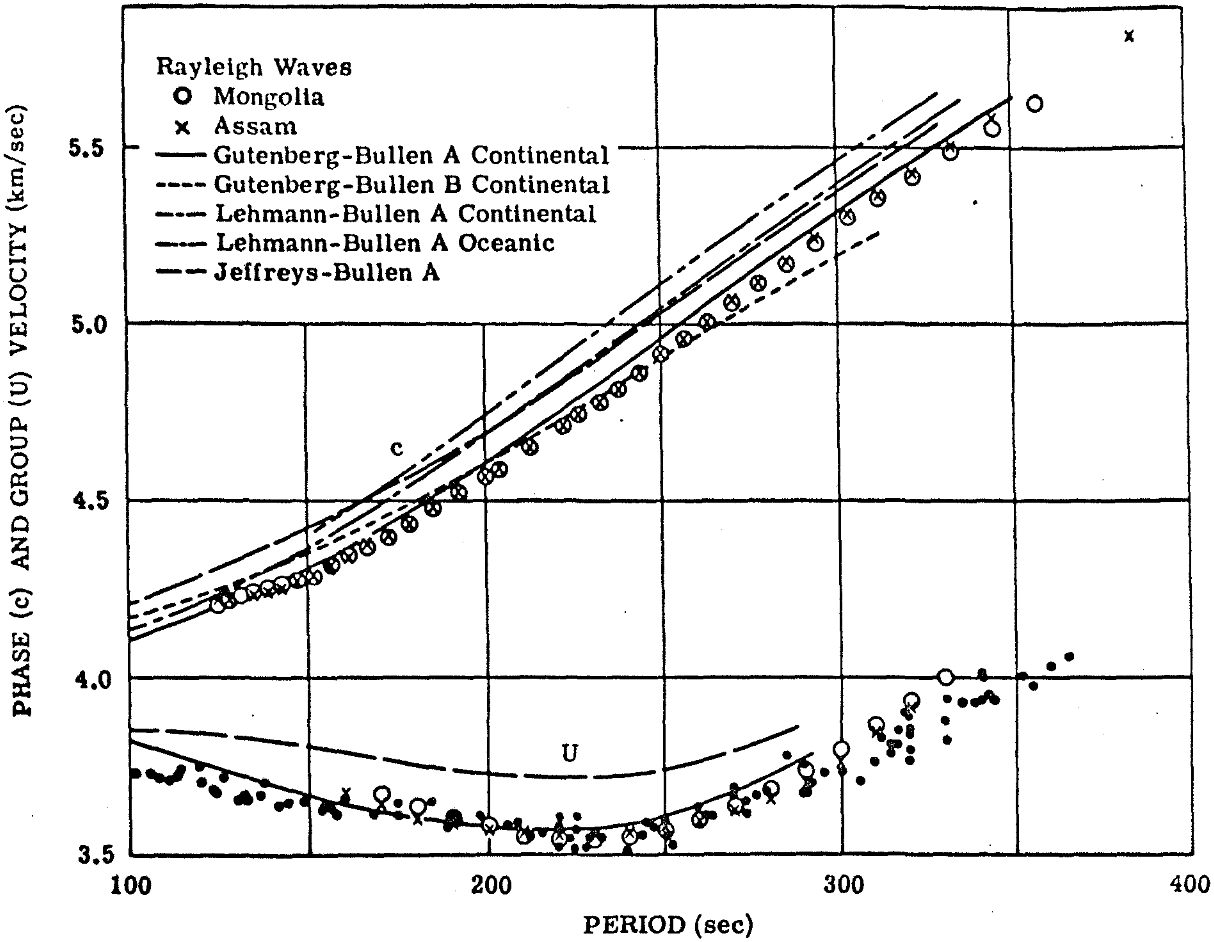


FIGURE 4.4. LAYER PARTIAL DERIVATIVES FOR GUTENBERG IV CONTINENTAL MODEL. Numbers below the curves refer to the depth of layer midpoint and layer thickness, both in kilometers.



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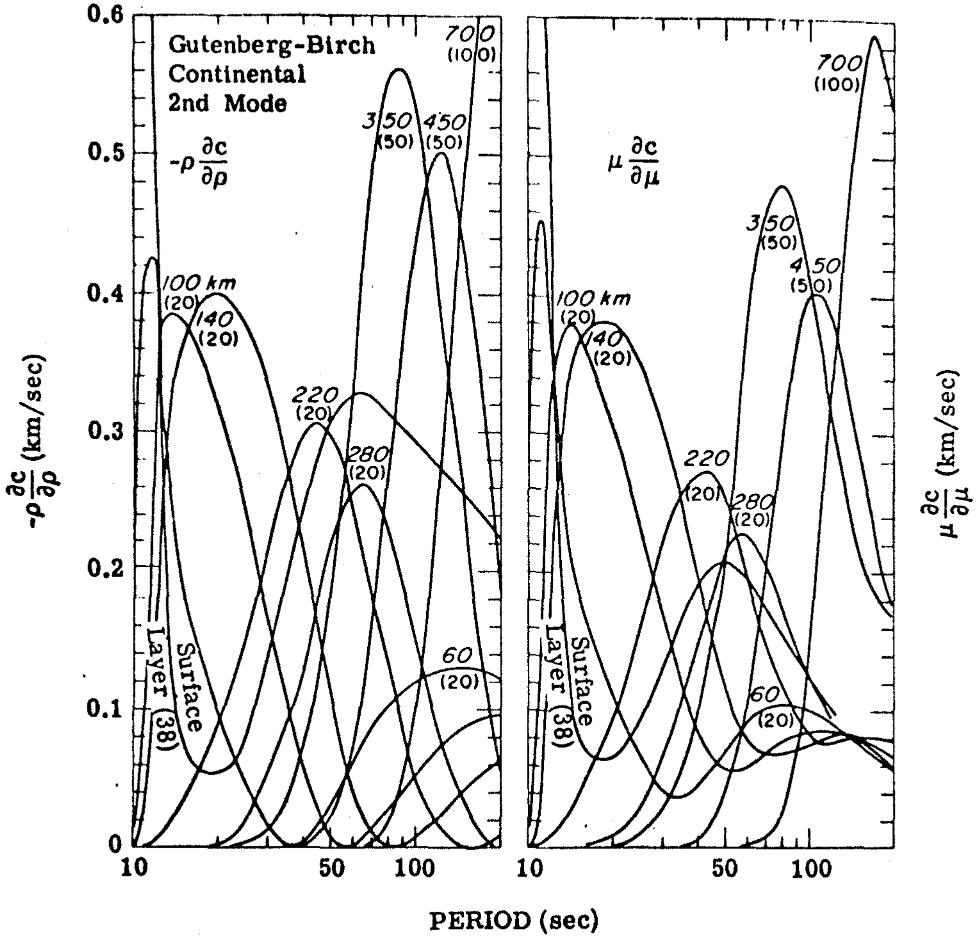

FIGURE 4.5. LAYER PARTIAL DERIVATIVES FOR THE SECOND LOVE MODE

Figure 4.6 shows successive stages in the evolution of an oceanic mantle structure using these techniques. The resulting structures, CIT 11 and CIT 11A, provide an excellent fit to oceanic Love-wave dispersion data, as will be shown later. Figure 4.7 compares CIT 11 with the standard models of Gutenberg and Jeffreys. CIT 11 has a low-velocity zone which is more pronounced than the corresponding feature of the Gutenberg model and a rapid change in properties near 400 km which is much more pronounced than the corresponding feature of the Jeffreys model. Clearly the upper 400 km has an average rigidity lower than standard models. Before taking this model too seriously an attempt was made to see which features of the CIT 11 structure could be suppressed without violating the dispersion data. The result was a structure designated CIT 13F. The dispersion results at various stages are shown in Figure 4.8. Figure 4.9 displays the dispersion results just discussed along with results for model 122 of Sykes et al. [10] (model 8099 of Reference 11) and available free oscillation and oceanic Love-wave dispersion data. Table 4.I summarizes the statistics for these models and several smooth polynomials providing a measure of the scatter of the data. The data used in this comparison are taken from Toksoz and Ben-Menahem [12] and Smith [13].

Figure 4.10 summarizes the present situation. We would expect mixed-path Love-wave data to fall between the oceanic and continental curves. Since this is not the case, our conclusion about a less rigid upper mantle under oceans might also apply to continents. In fact, an upper mantle under continents similar to the upper mantle structure of CIT 11 or CIT 13 is consistent with the mixed-path data. Long-period, purely continental dispersion data are needed to test this hypothesis.

Figure 4.11 shows the present status of Rayleigh-wave investigations. The consistency of the data, which represent various mixed paths, and the small differences between the theoretical curves indicate that path differences are almost negligible for the long periods considered here. This suggests that a purely oceanic path, for which we have no long-period Rayleigh-wave data, would yield results not too different from what is presented here. If this is the case, there is a real and systematic discrepancy between the data and all theoretical curves. In the absence of other information we would again speculate that the upper mantle is less rigid than previously determined. However, since CIT 11 was designed to satisfy Love-wave data, we are faced with a discrepancy between Love- and Rayleigh-wave results. It was this sort of discrepancy that led to the suggestion of an anisotropic upper mantle [14, 15].

Figure 4.12 compares the two oceanic models considered here and the 8099 model of Dorman et al. [11]. The shear velocity for CIT 11 decreases gradually from 4.61 km/sec at 26 km to its minimum value of 4.34 km/sec at 76 km. The velocity stays essentially constant to 156 km where it increases by 0.16 km/sec (3.7%) to 4.50 km/sec, and it then remains constant to a

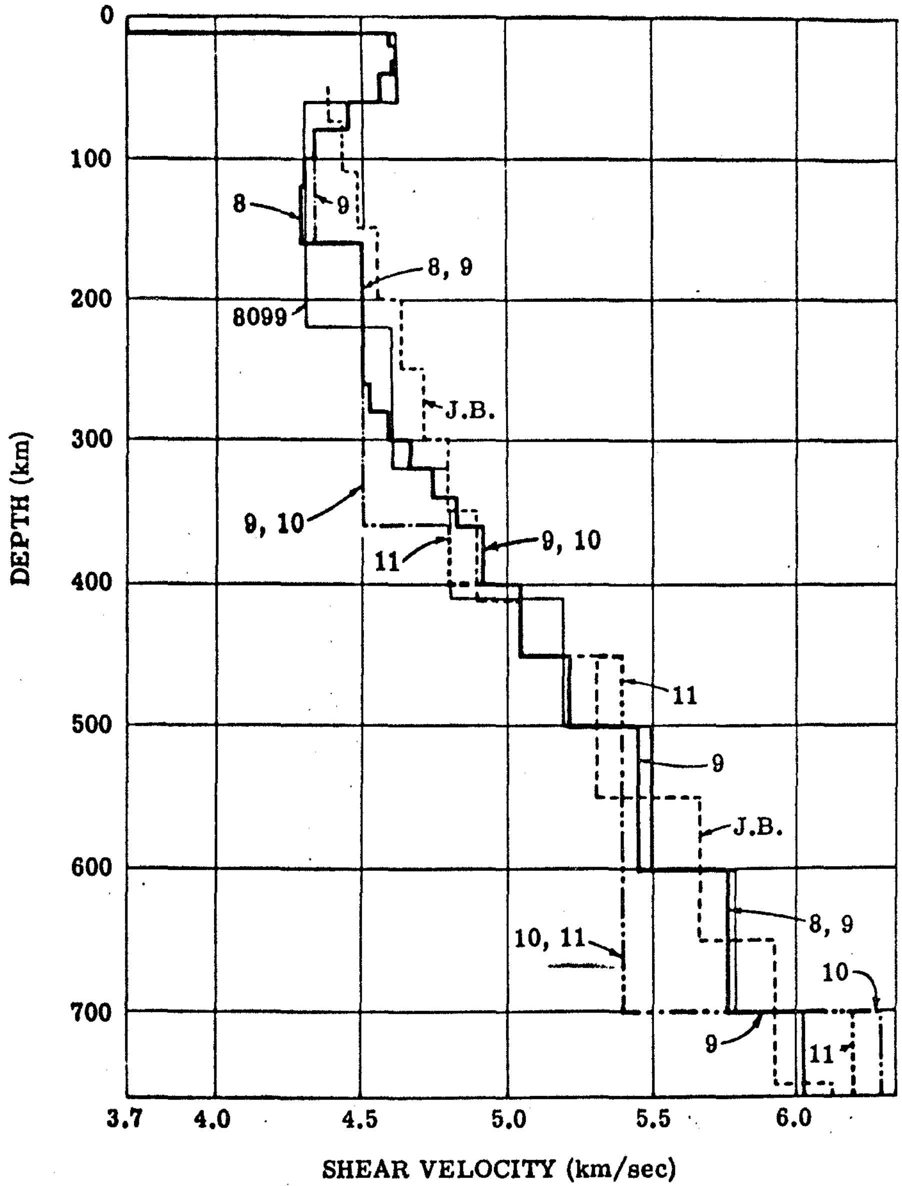

FIGURE 4.6. STAGES IN THE EVOLUTION OF AN OCEANIC MANTLE STRUCTURE [16]

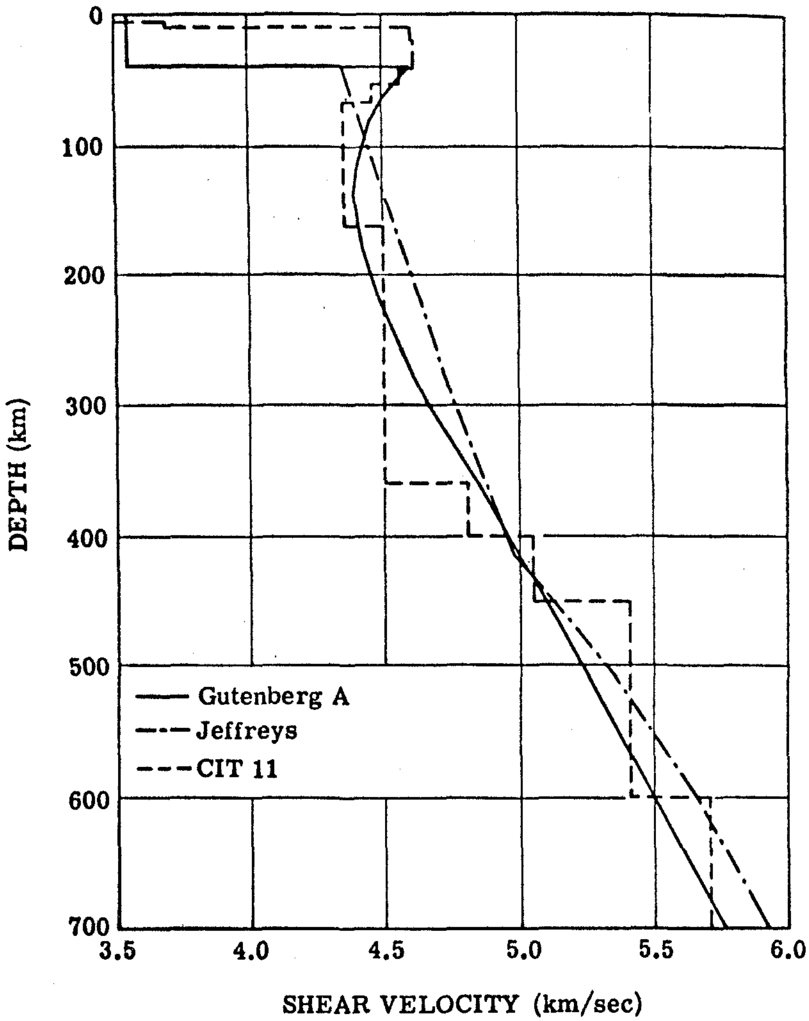

FIGURE 4.7. NEW EARTH MODEL, CIT 11, COMPARED WITH STANDARD STRUCTURES

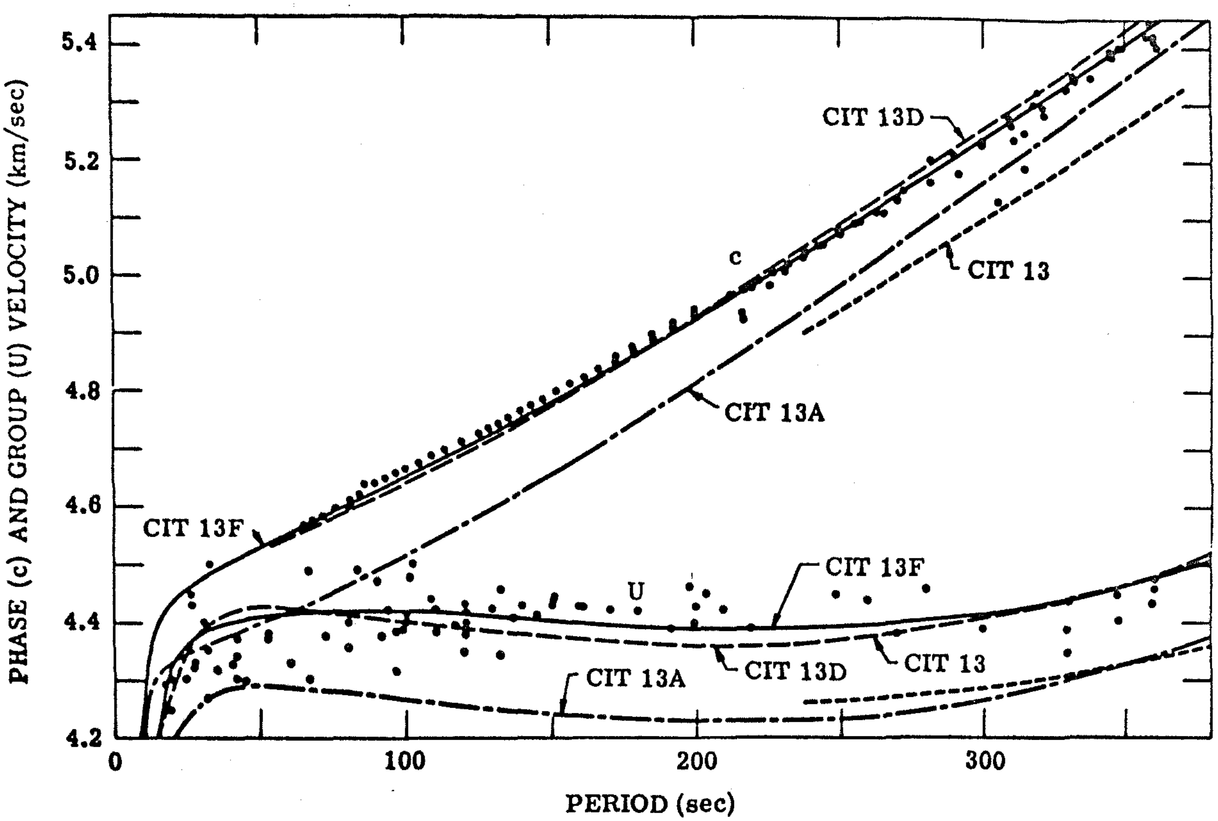

FIGURE 4.8. DISPERSION RESULTS OF CIT 13 EXPERIMENT

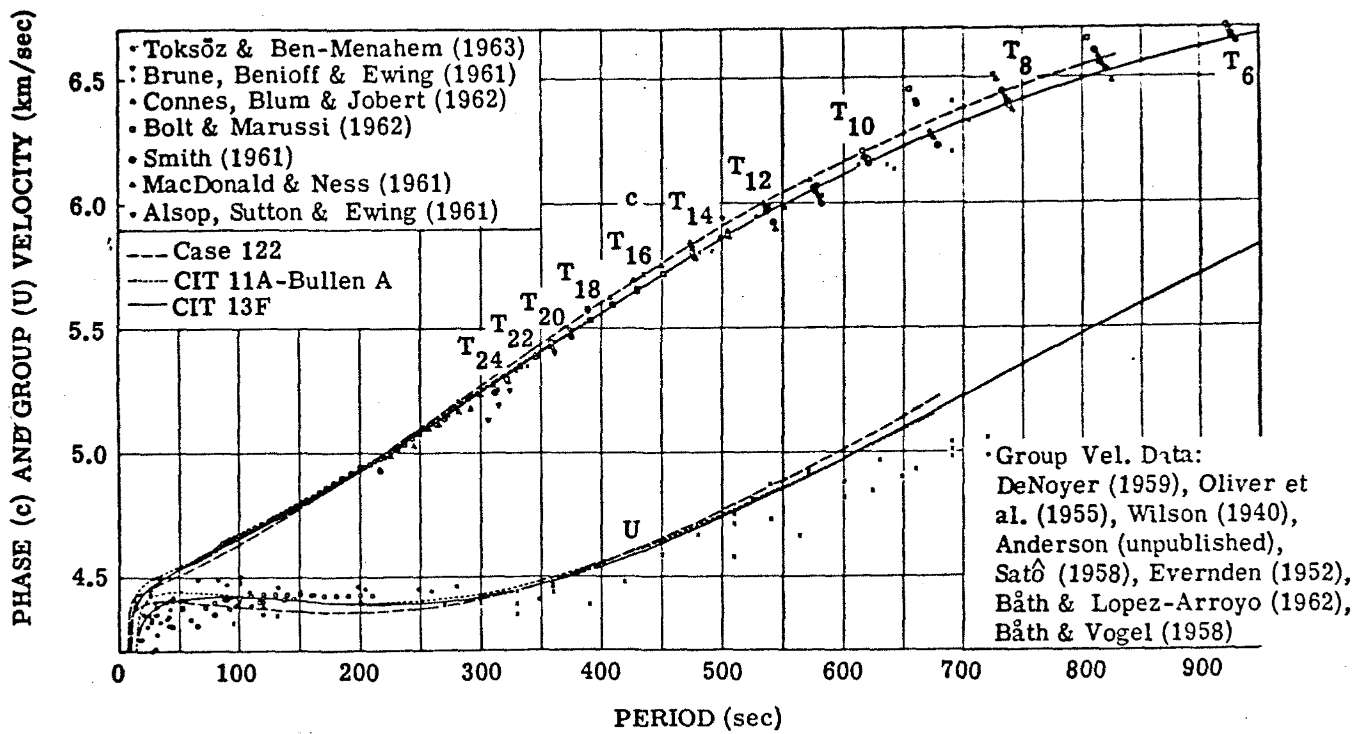

FIGURE 4.9. COMPARISON BETWEEN THEORETICAL CURVES AND LOVE-WAVE AND FREE OSCILLATION DATA

TABLE 4.I. COMPARISON BETWEEN THEORETICAL OCEANIC STRUCTURES AND AVAILABLE DATA

Case	Dispersion Data	Free Oscillation Data	RMS (km/sec)	Error
Polynomial (7)	X		0.003	0.06%
CIT 11A	X		0.0093	0.19%
CIT 13F	X		0.012	0.25%
122(8099)	X		0.025	0.55%
Polynomial (5)	X	X	0.017	0.27%
CIT 11A	X	X	0.019	0.33%
CIT 13F	X	X	0.020	0.36%
CIT 13G	X	X	0.019	0.32%
122(8099)	X	X	0.034	0.64%

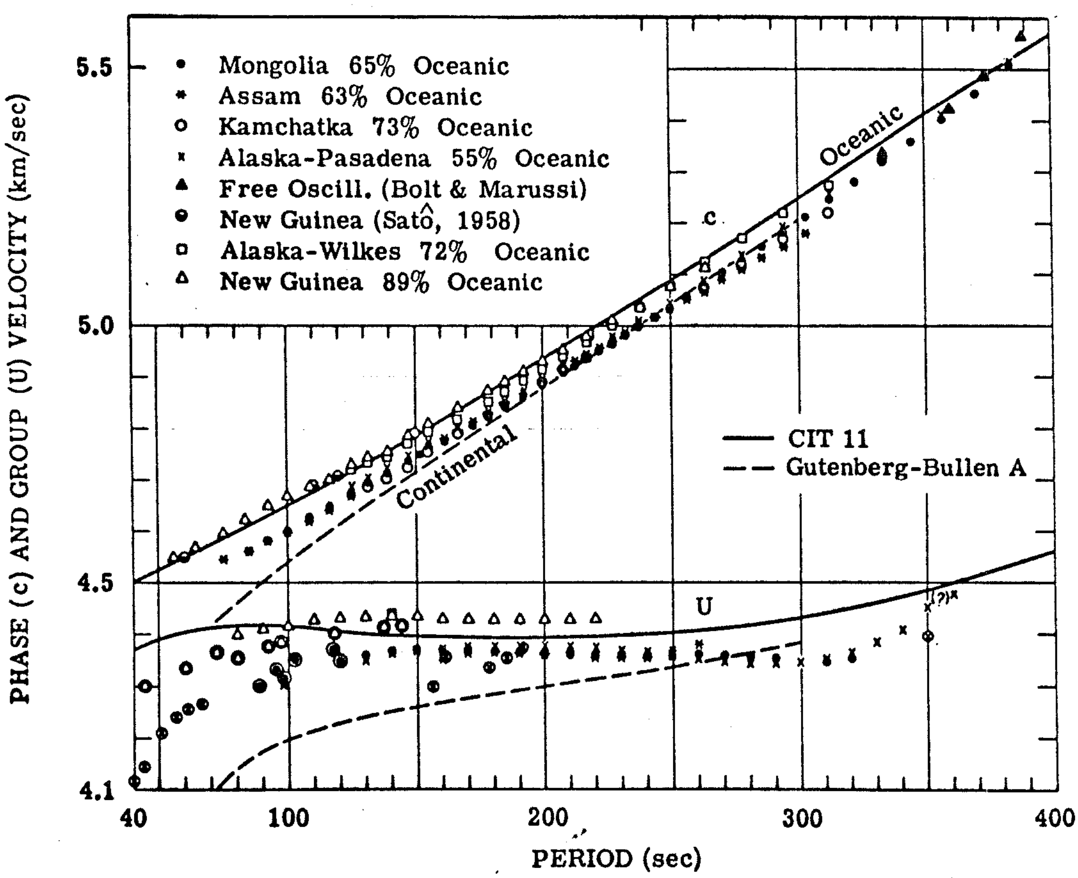

FIGURE 4.10. COMPARISON BETWEEN MIXED-PATH LOVE-WAVE DATA AND THEORETICAL "PURE PATH" CURVES

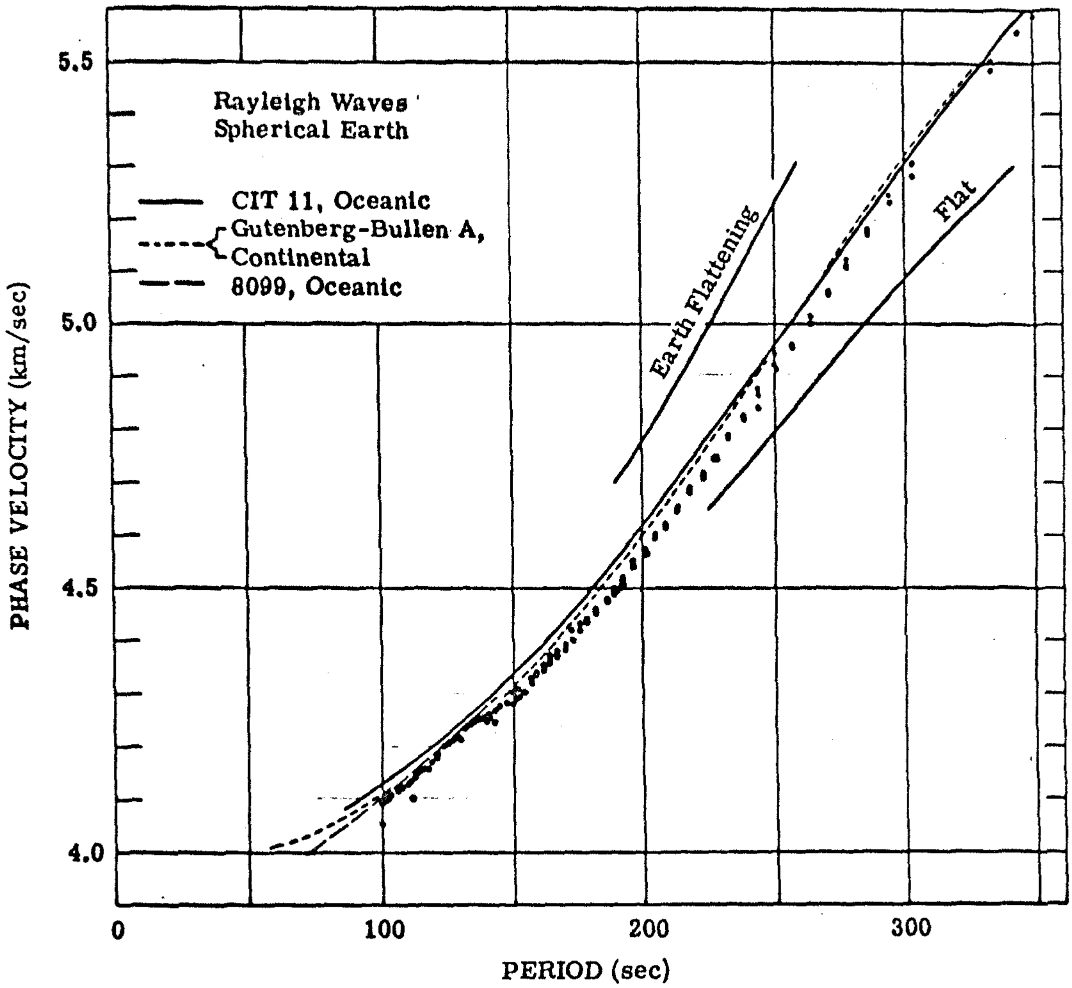

FIGURE 4.11. COMPARISON BETWEEN MIXED-PATH RAYLEIGH-WAVE DATA AND THEORETICAL CURVES

depth of 356 km. A very rapid increase in velocity sets in at this level, 0.9 km/sec in about 100 km. A second rapid change in properties sets in at almost 700 km, where shear velocity increases by about 0.8 km/sec in about 100 km. The velocity is monotonic thereafter, agreeing closely with the structures of previous studies, all of which are similar below some 800 km. CIT 13F developed from an attempt to suppress the major features which were a result of the CIT 11 experiment. In this model, which satisifes the Love-wave data almost as well as CIT 11, the low-velocity zone starts more abruptly and at a shallower depth. It also extends deeper and terminates more abruptly, and there is only one zone of anomalous velocity increase, from about 460 to 500 km. The large depth range of the low-velocity zone and its abrupt termination

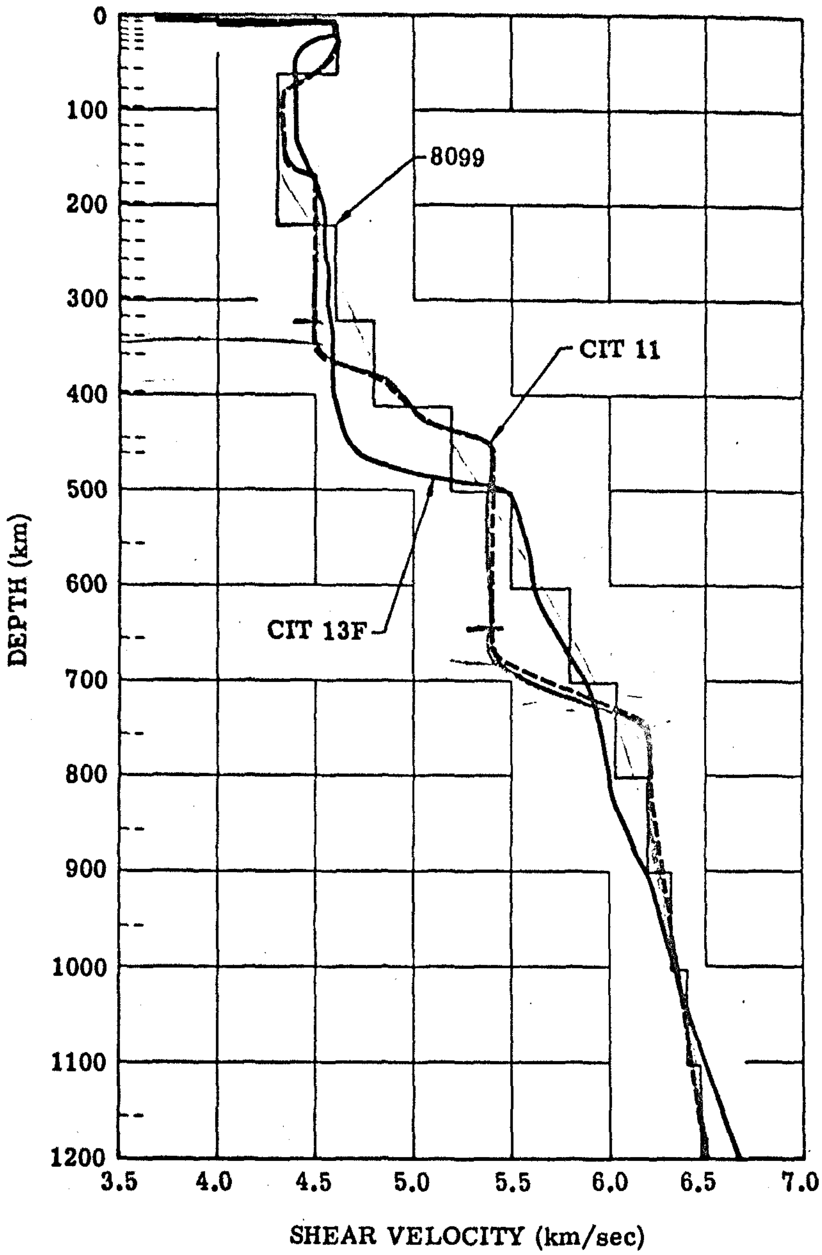

FIGURE 4.12. COMPARISON OF THREE OCEANIC MODELS

are features the two models share with each other, but not with previous models. The small increase in velocity between 150 and 200 km seems to be a necessary feature. CIT 11 satisfies travel-time data better than CIT 13F.

A picture of a zoned upper mantle emerges from this work. A synthesis of recent geochemical studies leads to the following highly speculative interpretation. The combined effects of temperature gradient, pressure gradient, and proximity to the melting point are consistent with a low-velocity zone as deep as 400 km. The low-velocity region may be chemically zoned, with the major compositional change taking place between 150 and 200 km. High temperatures and partial melting are both favorable for the diffusion required. A phase change of a minor constituent of mantle material, say Fe_2SiO_4, to a denser form is also a possibility. Between 350 and 450 km the anomalous increase in properties may be caused by the collapse of the familiar silicate structures to denser spinel or corundum type structures. The deeper discontinuity at about 700 km may be due to decomposition into periclase and either stishovite or a corundum form of pyroxene. As already stated, below some 800 km the mantle is homogeneous.

These conclusions can best be checked by a detailed study of higher modes. As a first step and as a guide in the design of appropriate experiments, dispersion has been computed for many higher modes for several earth models. Figure 4.13 shows results for the first eight Love modes for a continental model. Most of the so-called channel waves such as Sa, Li, and Lg can be explained by plateaus in the group velocity curves on this figure.

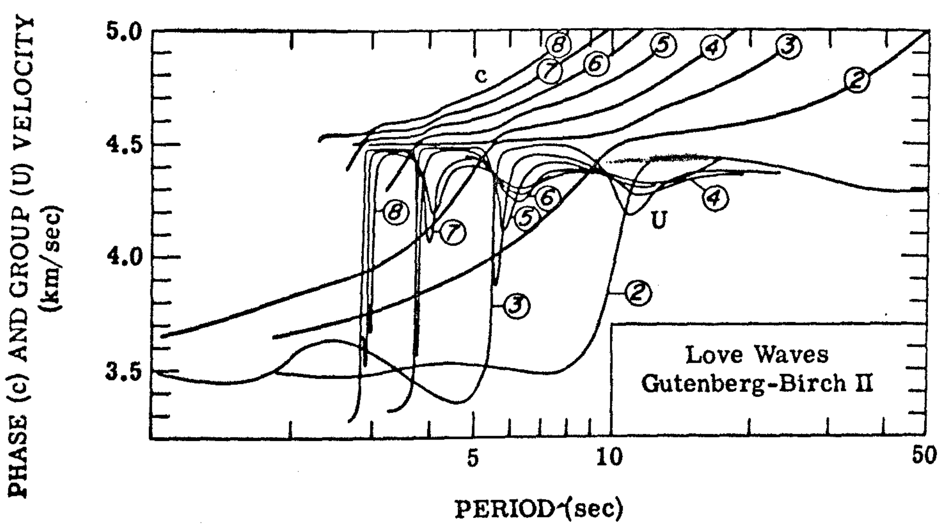

FIGURE 4.13. DISPERSION CURVES FOR THE FIRST EIGHT LOVE MODES FOR A CONTINENTAL MODEL

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