30
7-12-77

A.892 7/11

UCRL-52238

ON THE GEOPHYSICAL AND GEOCHEMICAL MODELS OF THE EARTH'S SHIELDS AND RIFT ZONES

D. H. Chung

February 25, 1977

Prepared for U.S. Energy Research & Development Administration under contract No. W-7405-Eng-48

LAWRENCE LIVERMORE LABORATORY
University of California/Livermore

NOTICE

NOTICE

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price: Printed Copy $; Microfiche $3.00

Page Range	Domestic Price	Page Range	Domestic Price
001–025	$ 3.50	326–350	10.00
026–050	4.00	351–375	10.50
051–075	4.50	376–400	10.75
076–100	5.00	401–425	11.00
101–125	5.50	426–450	11.75
126–150	6.00	451–475	12.00
151–175	6.75	476–500	12.50
176–200	7.50	501–525	12.75
201–225	7.75	526–550	13.00
226–250	8.00	551–575	13.50
251–275	9.00	576–600	13.75
276–300	9.25	601–up	*
301–325	9.75		

*Add $2.50 for each additional 100 page increment from 601 to 1,000 pages; add $4.50 for each additional 100 page increment over 1,000 pages.

Distributio.i Category
UC-11

LAWRENCE LIVERMORE LABORATORY
University of California Livermore, California 94550

UCRL-52238

ON THE GEOPHYSICAL AND GEOCHEMICAL MODELS OF THE EARTH'S SHIELDS AND RIFT ZONES

D. H. Chung

MS. Date: February 25, 1977

ON THE GEOPHYSICAL AND GEOCHEMICAL MODELS OF THE EARTH'S SHIELDS AND RIFT ZONES

Abstract

This report summarizes a collection, synthesis of, and speculation on, the geophysical and geochemical models of the Earth's stable shields and rift zones. There are two basic crustal types, continental and oceanic, and two basic mantle types, stable and unstable. The crustal types are distinguished by their thickness of crust, and the two mantle types are distinguished by their stability and upper mantle velocities and travel-time residuals. The stable mantle is characterized by relatively high P_n and S_n velocities and the frequent absence of geophysical evidences for low velocity zone and the unstable mantle by low P_n and S_n velocities and a pronounced low velocity zone in the upper mantle. Both the crust and upper mantle play a strongly interactive role with surface geological phenomena ranging from the occurrence of mountains, ocean trenches, oceanic and continental rifts to geographic distributions of earthquakes, faults, and volcanoes. On the composition of the mantle, there is little doubt regarding the view that olivine constitutes a major fraction of the mineralogy of the Earth's upper mantle. To simulate the elasticity and composition of the Earth's lower crust and upper mantle, a systematic study of the elasticity and equation-of-state properties of such materials as peridotites, eclogites, pyroxenites, amphibolites, and various gabbros and basalts is needed. Also needed are measurements of attenuation of acoustic waves at seismic frequencies in these solids and partially molten peridotites and in olivine single-crystals, because such data are necessary to determine the nature of phenomena responsible for the existence of a low velocity zone in the upper mantle.

Introduction

In the Earth, the propagation paths of seismic waves differ considerably from region to region due to variations of the structure and possibly the physical state and composition of the Earth's crust and upper mantle. Direct methods have to be devised to improve the present precision and reliability of seismic yields by detailed investigations of the regional variations of the "fine" structure, composition, and physical state of the Earth's crust and upper mantle. As indicated by the recent progress in observational seismology, the subject is basic to our understanding of all the seismic signals arriving at receiving stations.

As a part of the LLL Seismic Monitoring Research Program, this communication describes my collection, synthesis of, and speculation on, the geophysical and geochemical models of the Earth's stable shield areas and rift zones. Understanding of these tectonic regional features of the Earth is of practical concern to the LLL Seismic Monitoring Research Program (as well as other programs dealing with seismic yield verification of an explosion) because certain test sites (US and French) are located within rift zones or hot spots surrounded by stable shield areas. This research is directly related to improving our ability to estimate the yield of an explosion reliably.

Shields and Rift Zones: A Generalized Tectonic Classification

A generalized tectonic classification and the geophysical properties of the three most common crustal types (shields, rift zones, and for comparison, ocean basins) are presented in Table 1. In it, I used such parameters as crustal thickness, P_n and S_n velocities, travel-time residuals for P- and S-waves, tectonic characteristics, heat flow and Bouguer gravity anomalies, sediment thickness, and water depth (in accordance with Brune[1]).

Shields, within the context of plate tectonics, are very stable parts of the continents. Earthquake activities are low because few volcanoes have developed in these areas in recent earth history. The surface features include exposed deep metamorphic and plutonic rocks created through years of erosion processes. There are no thick sedimentary deposits younger than those of the Precambrian time. The typical shield structure has a crustal thickness of about 35 km, and the P- and S-wave velocities increase with depth from about 6.1 and 4.3 km/sec, respectively, to about 6.8 and 4.6 km/sec at a depth of 30 km or so. The P_n and S_n velocities are generally higher than in any other tectonic regions, typically 8.1 and 4.7 km/sec, respectively. Heat flow values are generally low and seldom exceed 1.0 HFU (1 HFU = 1 $\mu cal/cm^2$

Table 1. Tectonic classification and geophysical properties of stable shields, rift zones, and ocean basins of the Earth's surface.

Generalized crustal type	Shields	Rift zones	Ocean basins
Tectonic characteristic	very stable	unstable	very stable
Crustal thickness (km)	30 - 38	∿ 30	∿ 11
P_n (km/sec)	8.1 - 8.3	7.4 - 7.8	7.8 - 8.2
S_n (km/sec)	4.69 - 4.87	4.51 - 4.60	4.70 - 4.74
Travel time residuals (sec) for P-waves	∿ -1	∿ +1	∿ -1
Travel time residuals (sec) for S-waves	∿ -4	∿ +4	∿ -4
Heat flow (HFU)	0.7 - 1.2	1.7 - 2.5	∿ 1.3
Bouguer gravity anomaly (mgal)	-10 - -40	-200 - -300	+250 - +350
Surface geologic features	Little or no sediment, exposed batholitic rocks of Precambrian age. Very often, moderate thicknesses of post-Precembrian sediments visible.	More recent normal faulting, volcanism, and intrusion; high mean elevation; often rapid recent uplifting visible.	Very thin sediments overlying basalts, linear magnetic anomalies, no visible thick Paleozoic sediments.

sec). The Bouguer gravity anomaly is moderately negative (-10 to about -40 mgal at most).

The crustal type under rift zones includes such tectonically unstable areas as the Basin and Range Province, the Baikal Lake region, the Hoggar area, and the East Pacific Rise regions to name a few, and is characterized by recent normal faulting, volcanism, and intrusion that have resulted in a series of visible basins and ranges with a high mean elevation. The thickness of sediment varies from region to region, but is usually comprised of eroded volcanic materials.

The crustal thickness ranges from 20 to 30 km in most rift zones, except for Alpine regions where high mountains were created by rapid uplift. The P_n and S_n velocities are generally low, but no sharp boundaries in the velocity structures are apparent. Heat flow is very high in general, of the order of 2 HFU. The gravity anomaly is highly negative, -200 to about -300 mgal. Travel time residuals for both P- and S-waves are positive, as much as +1 sec for the P-waves. These observations indicate highly attenuating subsurface materials.

Ocean basins are regarded as stable parts of the Earth's crust overlain by water 4 to 5 km deep. The rocks are primarily basaltic overlaid with very thin sediment. The discovery in the late 1960's of remarkable linear magnetic anomalies paralleling oceanic ridges was a direct indication of sea-floor spreading and continental drift. Recent progress in research[2] of the oceanic basins indicate that a low-velocity crustal zone overlies a mantle with a P-wave velocity of about 7.8 to 8.0 km/sec. Major crustal changes occur from the ridge crest to the flank; in particular, at or near the crest crustal P-wave velocities are 5.2, 6.0, and 7.0 km/sec, and a low-velocity crustal zone overlies an anomalously low velocity mantle. This wedge of low-velocity crust thins with increasing age, so that a transition from anomalous crust at the ridge crest to normal oceanic crust occurs over a period of 5 to 6 million years. (Apparently, this low-velocity crustal wedge represents a magma reservoir with about 30% melt.) Most ocean basins are characterized by relatively high heat flow (~1.3 HFU), and high positive Bouguer gravity anomalies (+ 250 to + 350 mgal).

In summary, then, there are two basic crustal types: the continental and the oceanic, and two basic mantle types: stable and unstable, exemplified by the Precambrian shield areas and rift zones, respectively. The crustal types are distinguished by the crustal thickness as summarized in Table 1. The two mantle types are distinguished by their stability and upper-mantle velocities and travel-time residuals, the stable mantle being characterized by relatively high P_n and S_n velocities and the frequent absence of geophysical evidences for low velocity zone and the unstable mantle being characterized by low P_n and S_n velocities and a pronounced low velocity zone in the upper mantle. It is therefore apparent that the crust and upper mantle are closely linked in a tectonic sense.

On the Constitution of the Upper Mantle: Olivine Models

A perusal of the spectra of P-waves indicates that even explosions of very small magnitude are significantly richer in high frequencies (about 2 to 3 Hz) than are most earthquakes. Regional variations of the structure, composition, and physical state of the Earth's upper mantle present problems and it seems that the attenuation (and hence the frequency transmission characteristics) of the Earth's upper mantle varies significantly from place to place.

To what extent do we understand these regional variations and the constitution of the Earth's upper mantle? What are the most common rock types in these layers of the Earth's interior? What are the major mineral constituents in these rock types? These are among the more frequently asked questions by earth scientists. Numerous papers and books have been written; there are, however, as many variants of models as there are petrologists and geochemists.

What follows is my prejudice on the mineralogical composition of the average upper mantle, and it is founded on geochemical and geophysical data supported by theories and experiments of Solid Earth Geophysics. It is my hope and expectation that by exposure to the many interesting problems of our dynamic Solid Earth, experts in the LLL community will be enticed to engage in research on these topics.[3]

Olivine has long been recognized as a major mineral constituent of the upper mantle. This conjecture, originally based on inferences drawn from the study of stony meteorites, is supported strongly by the analysis of terrestrial rocks that appear to be either directly or indirectly derived from upper mantle sources. Numerous studies have described inclusions of garnet peridotite and eclogite associated with kimberlites (Nixon _et al._,[4] McGetchin and Silver,[5] Boyd and Nixon,[6] and Boyd[7]). Abundant field, petrological, and geochemical data support the proposition that kimberlites originate well within the upper mantle. Eruptive basalts frequently contain nodules which presumably represent, at least in some cases, pieces of wall-rock torn from the volcanic vent or conduit (Harris _et al._[8]). Generally, these nodules are ultramafic in composition (garnet and pyroxene peridotite, and rarely, eclogite) and thus contain a high percentage of olivine. In addition, alpine-peridotite ultramafic rock associations have frequently been described (Thayer,[9] Wyllie,[10] Moores[11]), based on their tectonic setting and textural relations, as direct indicators of upper-mantle composition. Of particular relevance to our present interests is the fact that in all of the foregoing "mantle-derived" materials, olivine is a dominant mineral component. Based on the foregoing sources of information, as well as on cosmic and solar elemental abundances, Ringwood[12,13] has derived a hypothetical composition for the primitive mantle and named it "pyrolite"; his pyrolite model (3 parts alpine-peridotite to 1 part Hawaiian basalt) contains 57 wt% $(Mg, Fe)_2SiO_4$ olivine.

The foregoing remarks serve to demonstrate the significance and importance of the mineral olivine to interpretations of the state and composition of the upper mantle. Most recent models of the physical properties for this region of Earth's interior rely heavily on the relevant material properties of olivine. A number of years ago Bernal[14] suggested that common olivine, which presumably occurs in the upper mantle, might transform into a spinel structure when an appropriate depth was reached. Later, Jeffreys[15] and Birch[16] expanded the olivine-spinel transition hypothesis as a qualitative explanation for the abnormally high P- and S-wave velocity gradients in the transition zone of the mantle. Within the last 10 or 15 years, as a result of continuing improvements associated with both seismic recording technology and data analysis methods, considerable refinement has been possible in the description of the velocity structure of the upper mantle and the nature of the transition zone. Perhaps the most significant discovery is the recognition of "fine-structure" within the transition zone. Several investigators (Anderson and Toksöz,[17] Johnson,[18] Archambeau *et al.*[19]) recognized a few years ago that the transition zone is characterized by two abrupt discontinuities in P-wave velocity, which occur around 400 km and 650 km. More recently, evidence has been presented (Helmberger and Wiggins,[20] Wiggins and Helmberger,[21] and Helmberger and Engen[22]) which suggests the presence of a third discontinuity in the region of 500 km. It is the 400 km discontinuity, however, that is directly relevant to the occurrence of olivine in the upper mantle. Extensive studies of the phase equilibria of ferromagnesian olivines in the recent past have demonstrated almost unequivocally that the 400 km discontinuity in the upper mantle may be identified with the transformation of $(Mg,Fe)_2SiO_4$ olivine into a "modified" spinel structure, thus verifying Bernal's earlier supposition.

The work which was largely responsible for establishing the olivine-spinel transformation as a valid explanation for the high-velocity gradient of the transition zone was initiated by Ringwood's[23] successful synthesis of the spinel polymorph of Fe_2SiO_4 at 600°C, followed by Boyd and England's[24] observations for Fe_2SiO_4 at 1500°C, and also in the phase stability experiments with Mg_2GeO_4 by Dachille and Roy[25]. Thereafter, numerous studies were carried out in order to define in a comprehensive and accurate manner the stability and phase relations of ferromagnesian olivine $(Mg,Fe)_2SiO_4$ at high temperature and pressure. Direct experimental determination of the olivine-spinel transition was at first restricted to the iron-rich end of the solid solution system because of the prevailing limitations of the available high-pressure apparatus. However, with the improvement of Bridgman anvil-type, high-pressure, high-temperature experimental devices, the equilibrium diagram for the olivine-spinel transformation was extended to within 20 mol % of the Mg_2SiO_4 end member (Sclar and Carrison,[26] Ringwood and Major,[27] and Akimoto and Fujisawa[28]). It was noticed also by several authors (Ringwood and Major,[27,29] Akimoto and Ida,[30] Morimoto <u>et al</u>.,[31] and Moore and Smith[32,33]) that the high-pressure modification on the forsterite end was that of an orthorhombic, "distorted" spinel structure, subsequently referred to as the "β-phase." Presently, accurate data are available which describe the olivine-spinel phase relations and the nature and width of the two-phase regions along isotherms of 800°, 1000°, and 1200°C (Ringwood and Major,[29] and Akimoto and Fujisawa[34]). The results of such studies indicate clearly, although some experimental discrepancies remain (Akimoto[35]), that within the range of temperature likely to occur in the upper mantle, forsterite-rich olivine transforms into a spinel or β-phase form at a pressure of around 120 kbar. In terms of depth, such a transformation pressure is consistent with the major seismic discontinuity at about 400 km in the mantle.

Considering the foregoing evidence of olivine as the dominant mineral constituent of the upper mantle, attention was directed to the physical properties of $(Mg,Fe)_2SiO_4$ and their relation to those physical characteristics which may be defined for the Earth's mantle from the analysis of geophysical observations. In a classic study, Anderson[36] calculated the properties of the upper mantle using a pure olivine model. His analysis rested on the phase equilibria data and elastic propert measurements for the olivine solid solution series available at the time. More recently, several investigators (Birch,[37] Chung,[38,39] Forsyth and Press,[40] and Graham[41]) have also examined the properties of the upper mantle with regard to olivine-dominant mineralogical models. Using more recent and complete sets of chemical and physical property data for olivine, these studies generally support the earlier speculations that the compressional and shear wave velocity profiles in the upper mantle may well be accounted for by a petrology that is characterized by olivine as a major component. Figure 1 illustrates this point. What is shown is the density and the bulk sound velocities determined for various olivines with Press's[42] Monte Carlo solutions for the Earth's mantle. We find that the slopes of olivine and olivine-transformed spinel with F_o/F_a ratios of about 95 F_o to 85 F_o are quite

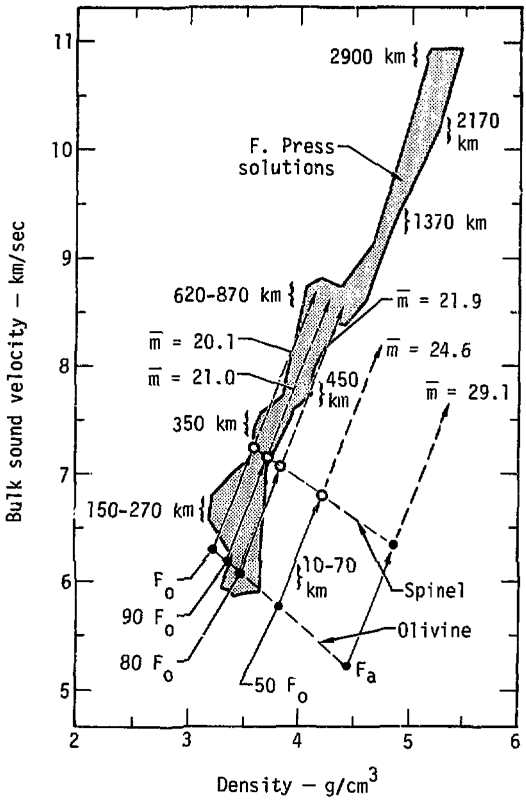

Fig. 1. Comparison of the laboratory bulk sound velocity-density relationship for olivine with F. Press's Monte Carlo successful solutions of the Earth data.

similar to large numbers of the Monte Carlo successful solutions in the region 150 to 870 km. Moreover, the most satisfactory Mg/Fe mol fraction is about 0.9, a value that is consistent with the average composition of the olivines associated with alpine peridotites and xenoliths and inclusions from kimberlites and basalt eruptives. Although recent investigators (Ahrens[43,44]) have considered the possible effects and the necessity of additional mineral components (primarily ortho-pyroxene and pyrope garnet), there is little doubt regarding the view that olivine constitutes a major fraction of the mineralogy of the upper mantle.

What kind of perturbations in composition, phase, and the physical state do we need to account for shield-rift-ocean differences? The answers to this question await discovery on the frontier of contemporary Solid Earth Geophysics. During the Penrose Conference on The Lithosphere-Asthenosphere Boundaries in November 1975, it became apparent that we know a great deal about the structure, composition, and the physical state of continents and very little about tectonics (including rift zones). In the oceans, the reverse is true. We need to know about both structure and tectonics of these areas and the implications of these on the development of the so-called "tectonosphere" if we are to progress to the next step.

In an earlier communication (Chung[45]) I presented a view toward the possible structure and composition of a region such as the Basin and Range Province. And I concluded that the present structure of the Basin and Range Province is possibly a result of rifting in the western conterminous United States; under it lies a mixed structure of old crust and mantle materials. The low velocity zone under the Basin and Range Province would then be caused by downward chemical transition from the sub-Moho pyrolitic mantle material into a plagioclase-rich ophiolitic (old oceanic crust and upper mantle materials) composition and associated melting, and then into a peridotitic composition at the bottom of the low velocity zone. This mixed material model, with partial melting, seems to explain the observed low P_n and S_n velocities and low-seismic Q in the region, as well as other geophysical observations.

The diagnosis of the composition and the physical state of the Earth's lower crust and upper mantle below the level of visual observation depends largely upon the correlation of seismic velocities and their attenuation data with laborat .y measurements of elasticity and attenuation and equation-of-state properties in samples of rock and mineral of known chemistry and mineralogy. The seismic structure does not, of course, depend upon the laboratory results; that is, the determination of wave velocities as a function of depth for a given locality depends only upon the seismic records, plus the judgment, skill, and general philosophy of the seismologist. Laboratory results are required for the translation of these numbers in terms of minerals or rocks, and for correlation with other physical properties. A systematic study of the elasticity and equation-of-state properties of such materials as peridotites, eclogites, pyroxenites, amphibolites, and various gabbros and basalts is needed to simulate the elasticity and composition of the Earth's lower crust and upper mantle. Measurements of attenuation of acoustic waves at seismic frequencies under controlled high pressure and temperature in these solids and partially molten peridotites, and in olivine single crystals are needed to determine the nature of phenomena responsible for the existence of a low velocity zone in the upper mantle.

References

1. J. N. Brune, in *The Earth's Crust and Upper Mantle*, P. J. Hart, Ed. Geophys. Monogr. 13 (American Geophysical Union, Washington, D.C., 1969).

2. "The Nature of the Oceanic Crust," a special issue of *J. Geophys. Res.*, 81, 4041-4421 (1976).

3. For enlightening discussions see C. L. Drake, Ed., *Geodynamics: Progress and Prospects* (American Geophysical Union, Washington, D.C., 1976), p. 238 ff.

4. P. H. Nixon, O. von Knorring, and J. M. Rooke, *Amer. Mineral.*, 48, 1090 (1963).

5. T. R. McGetchin and L. T. Silver, *Amer. Mineral.*, 55, 1738 (1970).

6. F. R. Boyd and P. H. Nixon, *Carnegie Inst. Washington Yearb.*, 72, 431 (1973).

7. F. R. Boyd, *Geochim. Cosmochim. Acta*, 37, 2533 (1973).

8. P. G. Harris, A. Reay, and I. G. White, *J. Geophys. Res.*, 72, 6359 (1967).

9. T. P. Thayer, *Int. Geol. Congr. 21 Rep. Sess. Norden.*, Pt. 13, 247 (1960).

10. P. J. Wyllie, *Mineral. Soc. Amer. Spec. Pap.*, 3, 3-32 (1970).

11. E. M. Moores, *Earth Sci. Rev.*, 9, 241 (1973).

12. A. E. Ringwood, in *Advances in Earth Sciences*, P. M. Hurley, Ed. (MIT Press, Cambridge, Massachusetts, 1966).

13. A. E. Ringwood, *Composition and Petrology of the Earth's Mantle*, (McGraw-Hill, New York, 1975).

14. J. D. Bernal, *Observatory*, 59, 268 (1936).

15. H. Jeffreys, *Mon. Notic. Roy. Astron. Soc.*, Geophys. Suppl., 4, 50 (1937).

16. F. Birch, *Geophys. Res.*, 57, 227 (1952).

17. D. L. Anderson and M. N. Toksöz, *J. Geophys. Res.*, 68, 3483 (1963).

18. L. Johnson, *J. Geophys. Res.*, 72, 6309 (1967).

19. C. B. Archambeau, E. A. Flinn, and D. G. Lambert, *J. Geophys. Res.*, 74, 5825 (1969).

20. D. V. Helmberger and R. Wiggins, *J. Geophys. Res.*, 76, 3229 (1971).

21. R. Wiggins and D. V. Helmberger, *J. Geophys. Res.*, 78, 1870 (1973).

22. D. V. Helmberger and G. R. Engen, *J. Geophys. Res.*, 79, 4017 (1974).

23. A. E. Ringwood, *Geochim. Cosmochim. Acta,* 15, 18 (1958).

24. F. R. Boyd and J. L. England, *Carregie Inst. Washington Yearb.,* 59, 48 (1960).

25. F. Dachille and R. Roy, *Amer. J. Sci.,* 258, 225 (1960).

26. C. B. Sclar and L. C. Carrison, *Trans. Amer. Geophys. Union,* abstract, 41, 207 (1966).

27. A. E. Ringwood and A. Major, *Earth Planet. Sci. Lett.,* 1, 241 (1966).

28. S. Akimoto and H. Fujisawa, *Earth Planet. Sci. Lett.,* 1, 237 (1966).

29. A. E. Ringwood and A. Major, *Phys. Earth Planet. Interiors,* 3, 89 (1970).

30. S. Akimoto and Y. Ida, *Earth Planet. Sci. Lett.,* 1, 358 (1966).

31. N. Morimoto, S. Akimoto, K. Koto, and M. Tokonami, *Science,* 165, 586 (1969).

32. P. B. Moore and J. V. Smith, *Nature,* 221, 653 (1969).

33. P. B. Moore and J. V. Smith, *Phys. Earth Planet. Interiors,* 3, 166 (1970).

34. S. Akimoto and H. Fujisawa, *J. Geophys. Res.,* 73, 1467 (1968).

35. S. Akimoto, *Tectonophysics,* 13, 161 (1972).

36. D. L. Anderson, *Science,* 157, 1165 (1967).

37. F. Birch, in *The Earth's Crust and Upper Mantle,* P. J. Hart, Ed. Geophys. Monogr. 13 (American Geophysical Union, Washington, D.C., 1969).

38. D. H. Chung, *J. Geophys. Res.,* 75, 7353 (1970).

39. D. H. Chung, *Geophys. J. Roy. Astron. Soc.,* 25, 511 (1971).

40. D. W. Forsyth and F. Press, *J. Geophys. Res.,* 76, pp. 7663 and 7972 (1970).

41. E. K. Graham, *Geophys. J. Roy. Astron. Soc.,* 20 (1970).

42. F. Press, in *The Nature of Solid Earth,* E. C. Robertson, Ed. (McGraw-Hill, New York, 1972).

43. T. J. Ahrens, *Phys. Earth Planet. Interiors,* 7, 167 (1973).

44. T. J. Ahrens, *Rev. Geophys. Space Phys.,* 13, 335 (1975).

45. D. H. Chung, *Tectonophysics* (to be published, 1977).

BHK/gw/wl/mg/gw