COMPOSITION OF THE UPPER MANTLE: GEOPHYSICAL TESTS OF TWO PETROLOGICAL MODELS

Jay D. Bass and Don L. Anderson

Seismological Laboratory, California Institute of Technology, Pasadena, CA 91125

Abstract. The elastic properties of candidate mantle phases are used to test the viability of olivine-rich (pyrolitic) and CaO + Al₂O₃-rich (eclogitic) assemblages for the mantle. High temperature adiabats for each phase of interest are constructed and compared to mantle seismic properties. Both pyrolitic and eclogitic assemblages satisfy the seismic properties between ~200 and 400 km depth. Between 400 and 670 km depth an eclogitic assemblage yields a superior match to velocities and density gradients. The 400 km seismic discontinuity may represent a chemical boundary between pyrolite and picritic eclogite ("piclo-

gite") rather than ol and opx. It is clearly desirable to test the viability of the gt-cpx hypothesis by direct comparison of the high pressure-high temperature velocities for such an assemblage with mantle velocity and density profiles. High velocity gradients in the transition zone may be explained by the transformation of Ca-rich cpx to majorite garnet. Seismic properties at the top of the lower mantle are consistent with pyrolite, piclignite or perovskite, implying that the 670 km discontinuity may be a chemical boundary.

Comparisons of laboratory elasticity data with seismic velocity profiles have been used in many studies to constrain the composition of the Earth's mantle. With few exceptions, it has been assumed a priori that the dominant minerals throughout the mantle are olivine (ol) and orthopyroxene (opx), coexisting with a small quantity of garnet (gt) and clinopyroxene (cpx). However, it remains to be demonstrated that ol-rich assemblages provide either a unique or the most satisfactory fit to the seismic data. Anderson (1976, 1979), Liu (1979), Lees et al. (1983), and Jeanloz and Thompson (1983) have discussed the difficulties of explaining the discontinuity at 670 km and the velocities in the transition region on the basis of phase relations in the ol and opx systems. A conclusion of the above studies is that the 670 km discontinuity may represent a chemical boundary. Differences in the Fe and/or Si (opx) content of the upper and lower mantle have been suggested, and Anderson (1979) proposed that the mantle between 220-670 km depth is dominated by gt + cpx (eclogite) rather than ol + opx. It is clearly desirable to test the viability of the gt-cpx hypothesis by direct comparison of the high pressure-high temperature velocities for such an assemblage with mantle velocity and density profiles. Although the stability fields and elastic properties of CaO-and Al₂O₃-rich high-pressure phases are less well constrained than those of ol and opx, sufficient information exists for silicates and analog compounds to examine the plausibility of an eclogitic region. In this paper we calculate the compressional (V₁) and shear (V₃) velocities, and density (ρ) of olivine, pyroxenes, garnets, and their poly-

tmorphs, at elevated temperatures and pressures. The properties of assemblages dominated by gt + cpx or ol + opx are then compared to observed mantle velocities and densities.

Copyright 1984 by the American Geophysical Union.

Paper number 410072.

Data Base

Although elasticity data for silicates and oxides has been steadily accumulating, a number of important phases remain uncharacterized. We have therefore relied on systematics to estimate the properties of some high-pressure phases. Data on analog compounds for all pertinent crystal structures are available and they yield consistent elasticity patterns. Bulk modulus (K) and rigidity (μ) are estimated from mean atomic weight or molar volume systematics and elastic constants of analog compounds. A complete discussion of our data base including T- and P-derivatives will be presented elsewhere (Bass and Anderson, in preparation).

The elastic and thermal properties and densities of ol, opx, gt, majorite (mj), (Mg,Fe)O, perovskite (pv), corun-
dum and stishovite have been summarized previously (O. L. Anderson, et. al., 1968; Jeanloz and Thompson, 1983; and references therein). Elasticity data are also available for jadeite (e.g., Hughes and Nishitake, 1963), β and γ spinels (Weidner et al., 1984; Sawamoto et al., 1984) and diopside (Levien et al., 1979). For some phases only static compression results are available (e.g. mj, MgSiO₃-pv) and in these cases measured values of K were used with velocity systematics to define μ for a given compound. In the absence of other constraints, both K and μ were estimated by velocity systematics. We note that perovskite-structure compounds exhibit well defined elasticity trends (Liebermann et al., 1977). For garnet-structures K (~170 GPa) and V₂/V₁ (~1.79) are virtually independent of composition and this has been assumed to apply to majorite (K = 220 GPa). Jadeite (jd), diopside (di), and opx, form majorite-garnet type solid solutions (Ringwood and Major, 1966, 1971). Molar volumes of the (hypothetical) majorite end-members are estimated to be 101.0 (jd) and 122.6 cc/mole (di) by assuming ideal mixing in solid solution. The post-majorite phase of jd-di solutions is thought to have a perovskite structure with end-member volumes of 32.1 (CaSiO₃, Ringwood and Major, 1971) and 24.9 cc/mole (NaAlSi₃O₈, Reid and Ringwood, 1976).

Results and Discussion

In Figure 1 we show V₁, V₃, and ρ for the low and high pressure phases of each component in our model mineral assemblages. The 1400°C adiabats were constructed using third-order Eularian finite strain theory (Sammis et al., 1970). All Fe-Mg silicates contain 10% Fe⁺⁺ component, except garnet (~20% almandite). Also shown are Earth model PREM (Dziewonski and Anderson, 1981) and other recent profiles (Grand and Helmburger, 1984; Walck 1984; Given and Helmbberger, 1980). A common feature is the high velocity gradient between 400 and about 670 km depth. The transition zone gradients are inconsistent with adiabatic compression of a homogeneous mineral assemblage and a broad phase transition is implied. The depth and breadth of the inferred phase change is an important constraint on the mineralogy in this region.
We compare two model mineral assemblages with the mantle data: one is pyrolite, which is predominantly ol with minor opx > gt = cpx (Ringwood, 1975), and the other is eclogitic, with gt = omphacitic cpx (jd + di) > ol or opx. The pyro-

litic assemblage has a low-pressure mineralogy of 23% di, 21% jd, 37% gt, 16% ol and 3% opx, and is thus a picritic-eclogite, or "piclogite" in composition. The piclogite gt contains slightly more Fe**+ than the pyro-

lite gt, consistent with eclogite gt from kimberlites.

We have assumed that across the 400 km discontinuity all ol is converted to \( \beta \), and opx is dissolved in the gt phase as mj. At 550 km, 60% of the opx has transformed to mj, which coexists with \( \gamma \) and opx-mj. At the bottom of the transition region all pyroxene is present as mj; below 670 km \( \gamma \) and gt-mj transform into pv-bearing assemblages. Although the phase relations for mineral compositions ap-

propriate to our pyrolite and piclogite assemblages are not well determined, the above sequence of phase transformation is consistent with the results of Jeanloz and Thompson (1983), Akaogi and Akimoto (1979) and Liu (1980). An important point is that di and jd are stable over a broader pressure range than opx. Phase changes in ol are very nar-

row relative to the width of the transition zone.

The results of our velocity (Voigt-Reuss-Hill averaging) and density calculations for piclogite and pyro-

lite are shown in Figure 1 and Table 1.

![Fig. 1: Vp, V, and density for various minerals. Earth model PREM is shown (heavy solid line) along with a range of velocities from other studies (dashed lines). The dashed density profile is a perturbation of PREM which has the same mean upper mantle + transition zone density. Adiabats are initiated at 1400°C (P = O). Circles and triangles indicate the properties of pyrolite and piclogite, respectively. The seismic profiles are substantially lower than pyrolite velocities and piclogite are small from 200-400 km and we consider both models to fit the velocity data in this region. Within the transition region (400-670 km depth), where we presume \( \beta \) and \( \gamma \) to be stable and the opx --- mj reaction complete, the densities of both assemblages compare well with the density of the mantle. However, the velocities of pyro-

lite and piclogite are quite different. Pyro-

lite yields S-velocities 9-17% higher and P-velocities 4-5% higher than the seismic values. By contrast, \( V_s \) and \( V_p \) for piclogite provide a close match to the seismic velocity.

The variation of density with depth is poorly deter-

mined with available data but the average mantle density between 220 and 670 km is well constrained (Jordan and Anderson, 1974). The average densities of pyrolite and piclogite assemblages are both within 1% of PREM over this depth interval indicating that density does not provide a basis for distinguishing the two compositional models. Between 400 and 670 km depth pyro-

lite and piclogite are similar and slightly lower than PREM suggesting that PREM is too dense in this region. The dashed line in Fig 1 shows a modification of PREM with the same average density between 220-670 km.

Phase changes in pyrolite cannot explain the 400 and 670 km discontinuities (Table 1). It is traditional to refer to the 400 km discontinuity as the "olivine-spinel" phase change but the calculated velocity jumps in olivine are more than twice as high as observed. At 670 km the ob-

served velocity increases by 5% and the boundary is sharp, rather than diffuse as predicted for an ol or opx phase change (Jeanloz and Thompson, 1983).

It is difficult to match the high velocity gradients ob-

served between 400 and 670 km with a pyro-

litic model. The transition zone gradients are much higher than is charac-
The persistence of a piclogite transition zone and a lower mantle at 670 km would require that the transition zone and lower mantle are chemically distinct regions. The persistence of a piclogite transition zone and a lower mantle is consistent with piclogite. The seismic properties between piclogite and pyrolite are generally consistent with piclogite. Given, J. and D. Helmberger, Upper mantle structure of northwestern Eurasia, J. Geophys., Res., 85, 7183-7194, 1980.

Table 1. Compressional velocity, $V_p$, shear velocity, $V_s$, and density, $\rho$, for three mineral assemblages and the Earth's mantle. Velocity in km/sec; $\rho$ in g/cm$^3$.

| Depth (km) | Piclogite | | | Pyrolite | | | | Perovskite | | | | Earth | | |
| 220 | 8.35 | 4.67 | 3.50 | 8.27 | 4.60 | 3.40 | 8.35 | 4.64 | 3.44 | | | | | | |
| 400 | 8.82 | 4.86 | 3.65 | 8.80 | 4.81 | 3.54 | 8.82 | 4.77 | 3.54 | | | | | | |
| 550 | 9.85 | 5.35 | 3.86 | 10.17 | 5.51 | 3.87 | 9.90 | 5.37 | 3.91 | | | | | | |
| 650 | 10.29 | 5.50 | 3.96 | 10.50 | 5.63 | 3.95 | 10.26 | 5.56 | 3.99 | | | | | | |
| 711 | 10.73 | 5.90 | 4.36 | 10.70 | 5.92 | 4.32 | 10.92 | 6.01 | 4.37 | 10.75 | 5.95 | 4.38 | | | |


(Received December 15, 1983; accepted January 10, 1984.)