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Petrology of a dynamic Earth's Mantle[1])

By Alan Bruce Thompson[2])

ZUSAMMENFASSUNG

Neue Ergebnisse der experimentellen Petrologie bestätigen, dass die seismische Diskontinuität in 380–425 km Tiefe im Erdmantel mit dem Phasenübergang der α zur β-Form von (Mg, Fe)$_2$SiO$_4$ übereinstimmt. Im weiteren ist der Phasenübergang (Mg, Fe)$_2$SiO$_4$ (γ-Spinell) = (Mg, Fe)SiO$_3$-Perovskit + (Mg, Fe)O-Magnesiowüstite ein sehr plausibler Kandidat für die seismische Diskontinuität in 650–690 km Tiefe. Wenn diese zwei prominenten seismischen Diskontinuitäten, welche die Mantel-Übergangszone begrenzen, durch Mineralreaktionen erklärt werden können, ist die Annahme eines Unterschiedes in der chemischen Zusammensetzung des Erdmantels oberhalb und unterhalb von 670 km Tiefe nicht nötig. Ohne chemische Grenzschichten ist eine den gesamten Erdmantel umfassende Konvektion (von Kern-Mantel-Grenze bis zur Lithosphäre) möglich.

Leider stimmen die gemessenen oder geschätzten Dichtewerte und die elastischen Moduli der entsprechenden Mineralien nicht ganz mit den seismischen Beobachtungen für den Tiefenbereich von 600 bis 700 km überein. Deshalb kann bis heute eine Änderung im Chemismus in der Mantel-Übergangszone nicht ausgeschlossen werden. Gemäss verschiedenen Modellen würde eine solche chemische Grenzschicht zwei voneinander fast unabhängige Konvektionssysteme im Erdmantel trennen.

Neue Beobachtungen mit Hilfe der seismischen Tomographie zeigen in einigen Bereichen des Erdmantels lokale Störungen des seismischen Geschwindigkeitsfeldes bis in 1700 km Tiefe, welche sehr gut mit bestimmten subduzierten, ozeanischen Platten übereinstimmen. In anderen Mantelbereichen sind subdizierte Platten mit Störungen in der Nähe der Kern-Mantel Grenze korrelierbar. Es wird vorgeschlagen, dass aufsteigende Konvektionsströme von warmem, leichtem Mantelmaterial ab und zu die Übergangszone des Mantels durchdringen können und als sogenannte «Heisse Flecken» (hot spots) in der Lithosphäre erscheinen.

ABSTRACT

Recent results from high-pressure experimental petrology, using the uniaxially-driven split-sphere apparatus, confirm that the 380–425 km seismic discontinuity can correspond with the α to β transition in (Mg, Fe)$_2$SiO$_4$. The 650–690 km seismic discontinuity is plausibly explained by the transition (Mg, Fe)$_2$SiO$_4$ (γ-Spinel) = (Mg, Fe)SiO$_3$-Perovskite + (Mg, Fe)O-Magnesiowüstite. However, the lack of good matching of experimentally determined elastic parameters and densities with those deduced from seismology cannot yet preclude a chemical stratification between transition zone and lower mantle (650–690 km). Ca-Al-Mg-Fe silicate-perovskites plus (Mg, Fe)O-magnesiowüstite appear to dominate the mineralogy of the lower mantle down to near 2,900 km. Depending upon the chosen values of densities and elastic moduli of minerals compared with those deduced from seismology, the lower mantle need not be slightly richer in Si and Fe than the upper mantle.

One current view of the Earth's Mantle appears to support a two-layer mantle convection system, above and below the 650–690 km discontinuity. However, some studies indicate occasional upwards leakage of plumes through the transition zone. Such plumes could orginate near the core-mantle boundary, and may be the cause of near-surface hot-spots and flood basalts. Downward slab penetration through the 670 km discontinuity, apparently at least down to 1,700 km in the lower mantle, could certainly compensate the upflow by deep mantle-plumes.

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Introduction

The Earth has at least two major boundary layers. The crust is a worldwide *chemical boundary layer,* with depth to Moho of 5 to 8 km under the ocean basins and 30 to 80 km under the continents. The Earth's lithosphere consists of the crust and part of the mantle (extending to about 125 km beneath the ocean basins and to deeper than 200 km beneath the continents) and constitutes a *thermal boundary layer* capping the convecting asthenospheric mantle.

The lower mantle is separated from the core by the D″ layer, of 200 to 300 km thickness. This layer is most likely a chemical boundary as well as a thermal boundary. Magnetic field perturbations near the core-mantle boundary (Bloxham & Gubbins 1987) appear to indicate a mass-flux from core to mantle.

The density-seismic velocity systematics obtained from seismological observations of the Earth's Mantle do not show smooth increases with depth. Quite a number of seismic discontinuities have been observed at particular depths. The first-order discontinuities between 380 to 425 km (the *"400 km"*) and between 650 to 690 km (the *"670 km"*) are the most prominent and, as a result, are the best investigated. The second-order discontinuities at about 200, 550, 1,100, 1,250, 1,600 km are less well studied and their existence as global discontinuities is disputed (see summaries by Ringwood 1975 and Anderson 1989b).

Most recent work has continued to focus on whether:

(1) the prominent seismic discontinuities most likely represent chemical/thermal boundary layers – in which case the present mantle is probably concentrically layered with different chemistries and with largely separate convection systems; or

(2) whether the seismic discontinuities reflect mineralogical phase changes- thus indicating that the mantle chemistry need not vary abruptly, and that convection can be mantle wide.

Major advances in the understanding of the processes likely to be occuring in Earth's Mantle have taken place since the publication of two important books in the 1970's (Wyllie 1971, Ringwood 1975). Some of these advances, achieved through much improved experimental techniques, data accumulation and interpretation, are summarised in the comprehensive review by Silver et al. (1988) and the recent book by Anderson (1989b).

Recent interpretations of the major seismic discontinuities in the mantle

The interpretation of particular seismic discontinuities as being the result of mineralogical phase transformations hinges on the depth and width of the discontinuity observed by seismology, and the matching of elastic and other physical parameters across the discontinuity with the pressure-temperature location of a suitable mineral reaction obtained by experimental petrology.

The "400 km" seismic discontinuity has been reported to be 5 to 15 km wide by Fukao (1977). The experimental data on the α to β transition in $(Mg, Fe)_2SiO_4$ (eg. see Akimoto & Fujisawa 1968, Ringwood 1975), was interpreted by them and Jeanloz & Thompson (1983), Liu & Bassett (1986), Bina & Wood (1987) among others, as being adequate to explain the width and depth of the 400 km seismic discontinuity. In contrast, Bass & Anderson (1984) and Anderson & Bass (1986), using the seismological observation by Leven (1985) of a width of about 6 km for the 400 km discontinuity, suggested that the α to β transition in (Mg, Fe)$_2$SiO$_4$ was too spread out and that this discontinuity should be interpreted as a chemical boundary.

Even though by the early 1980's, the 400 km seismic discontinuity in the Earth's Mantle could apparently be related to likely mineralogical phase changes (in Mg_2SiO_4-Fe_2SiO_4; α to β or γ phases), the 670 km discontinuity could not (eg. Jeanloz & Thompson 1983). The most likely phase transition of γ-spinel [(Mg, Fe)$_2$SiO$_4$] to perovskite [(Mg, Fe)SiO$_3$] plus magnesiowüstite [(Mg, Fe)O], investigated by laser-heated diamond-anvil experimental devices, did not occur at the required pressures and temperatures, and the reaction interval was apparently too wide (Jeanloz & Thompson 1983, Anderson 1984, 1987, Takahashi & Ito 1987).

These results were thus interpreted to mean that the 670 km seismic discontinuity must represent a chemical boundary layer, separating the upper and lower mantle (Jeanloz & Richter 1979, Herzberg 1984, Ito et al. 1984, Weidner 1986, Anderson 1987a, Ringwood & Irifune 1988, Sun 1989).

A chemically stratified mantle?

At present, a chemically-stratified mantle maintained by two isolated convecting systems is apparently supported by modelling of the observed isotopic and trace-element evolution of mantle-derived magmas (Ohtani 1984, O'Nions 1987, Herzberg et al. 1988, Galer et al. 1989, Hart & Zindler 1989). The deduced 30 volume-% as the mantle magma source region corresponds to the volume of the mantle above 670 km (Wood 1989).

Chondritic meteorites support a bulk-mantle composition which is richer in Fe and SiO_2 than that deduced for the upper mantle (Ringwood 1975, Anderson 1989, 1989a). Consequently, higher (Mg + Fe)/Si and Fe/Mg ratios in the lower mantle would result in greater amount of the (Mg, Fe)SiO$_3$ component relative to the (Mg, Fe)$_2$SiO$_4$ component (and with Fe-richer compositions) in the lower mantle (> 670 km) compared to the upper mantle (< 400 km), (see Anderson 1989, 1989a, Ringwood 1989).

Earthquakes have still not been observed from deeper than about 700 km. This is also taken as an argument by some (eg. Anderson 1989) that slab penetration through the 670 km seismic discontinuity does not occur. Strictly isolated upper from lower mantle convecting regions, separated by a boundary layer near 670 km, would cause subducted oceanic slab material to pond at this depth (Hager 1984, Kerr & Lister 1987, O'Nions 1987, Christensen 1988, Ringwood & Irifune 1988, Gurnis & Hager 1988). Also the rise of deeper mantle diapiric jets through the transition zone between 400 to 670 km, would be similarly inhibited (Jeanloz & Richter 1979, Schubert 1979, Peltier 1981, Jeanloz & Thompson 1983, Hager 1984, Loper & McCartney 1986, O'Nions 1987, Houseman 1988, Davies 1989, Hager & Clayton 1989).

Recent observations of seismic anomalies deeper than 1,000 km (Creager & Jordan 1986, though disputed by Zhou & Anderson 1989; see debate outlined by

KERR 1990), appear to suggest that the presumed boundary layer at 670 km is not efficiently maintained in all parts of the present mantle.

Aspherical structures in the depth range 700 to 1,700 km in some parts of the mantle, are considered by JORDAN et al. (1989) to reflect slab flux through the 670 km discontinuity (shown schematically in Fig. 1). Other instances of possible disruption of one or more boundary layers in the mantle are supported by observations obtained from seismic tomography that reveal apparent lateral heterogeneities in seismic velocity in the lower mantle (DZIEWONSKI & WOODHOUSE 1987, ELLSWORTH et al. 1985, HAGER 1984, HAGER et al. 1985, YOUNG & LAY 1987), and also in the upper mantle (HERZBERG 1984, ANDERSON 1987). However, greater seismic resolution in seismic velocity contrast with reference to subducted slabs and possible rising plumes, is needed to verify these assertions.

Mineral reactions and the sharpness of seismic discontinuities

Recent measurements of the elastic properties of the α, β and γ phases of Mg_2SiO_4-Fe_2SiO_4 (BINA & WOOD 1984, WEIDNER 1986), indeed support the other experimental studies, that the 400 km seismic discontinuity can be equated with the transition from α to β. However, ANDERSON (1989b) still maintains that the observed seismic velocity jump at the 400 km discontinuity is smaller than predicted for the olivine-spinel transition and requires the presence of large quantities of a high-pressure pyroxene-garnet phase in this region of the mantle.

According to some seismological investigations, the 670 km discontinuity is seismically sharp, occurring over 4 to 5 km (LEES et al. 1983, ANDERSON 1989b). Earlier experimental results obtained with laser-heated diamond anvil devices (see summary by JEANLOZ & THOMPSON 1983) indicated a large pressure interval (1.5 to 2.0 Gpa, about 50 km) for the γ-Spinel = Perovskite + Magnesiowüstite (γ-Sp = Pk + Mw) transition. Such a width, implied by these experimental data, then precluded this phase change as a possible explanation for the 670 km discontinuity (JEANLOZ & THOMPSON 1983).

New results from high-pressure experimental petrology

The new experimental results of KATSURA & ITO (1989) on the α to β transition in $(Mg, Fe)_2SiO_4$ using a uniaxially-driven split-sphere apparatus, together with the thermochemical calculations by AKAOGI et al. (1989) based upon new calorimetric measurements on the α to β to γ transitions, are certainly consistent with the α to β phase change being responsible for the 400 km discontinuity, with a width of 13 to 23 km. The data further imply an average present mantle temperature of about 1,400 °C at 390 km.

The new experimental work of ITO & TAKAHASHI (1989), also using a uniaxially split-sphere apparatus, suggests that spinel (Sp, γ) with composition between Mg_2SiO_4 and $(Mg_{0.8}Fe_{0.2})_2SiO_4$ decomposes to perovskite (Pk, ~ $(Mg_{0.9}Fe_{0.1})SiO_3$) plus magnesiowüstite (Mw, ~ $(Mg_{0.6}Fe_{0.4})O$) over a very narrow pressure interval (~ 0.15 GPa at 1,600 °C). ITO & TAKAHASHI's (1989) results indicate that the sharp transition occurs at 23.1 Gpa at 1,600 °C. This pressure is slightly lower than that at the 670 km discontinuity (23.7 Gpa, DZIEWONSKI & ANDERSON 1981), but certainly lies within the pressure unvertainly of the experiments. The negative Clapeyron slope (dT/dP) for the reaction γ-Sp = Pk + Mw would imply a temperature of 1,400 °C at 23.7 Gpa, significantly lower than the 1,600 °C expected at this depth in the mantle (JEANLOZ & RICHTER 1979, AKAOGI et al. 1989).

Thus the new experimental investigations do suggest that the γ-Sp = Pk + Mw phase change is most likely involved in the 670 km seismic discontinuity, but exactly in what amount is still not fully resolved. The phase relations among Ca-Mg-Fe perovskites and the role of Al in stabilising garnet (majorite component) and of Ti perhaps stabilising perovskite (?), certainly needs further experimental investigation. Possible transitions in majorite-garnet (RINGWOOD 1975, JEANLOZ & THOMPSON 1983, ANDERSON 1989b) may produce a broader transition superimposed on the comparatively sharp γ Sp = Pk + Mw phase change. This could result in spreading out the width, the depth range and the seismic intensity of the 670 km discontinuity. Additional seismological experiments directed at determining the sharpness and depth of the 670 km discontinuity (eg. RICHARDS & WICKS 1990) are clearly worthwhile.

Consequently on the basis of results from high-pressure experimental petrology, the 670 km discontinuity appears to be coincident with the γ-Sp = Pk + Mw phase change, probably displaced due to Ca, Al and Ti in silicate-perovskite. It is also possible that additional mineralogical phase changes occur in the pyroxene-garnet components as well JEANLOZ & THOMPSON 1983, JEANLOZ 1989, WOOD 1989). Whether the 670 km seismic discontinuity represents in addition a chemical boundary layer, has been considered in terms of the density and elastic moduli values for the participating phases. As implied below, a chemical discontinuity, with a density change of 2% or more could occur almost any depth within the transition zone, or even deeper (KNITTLE et al. 1986).

Elasticity and density of minerals and the petrology of the lower mantle

Elastic moduli of several high-pressure minerals have been measured on quenched samples or in-situ in high pressure-temperature devices. These have been combined with seismic observations and the results from experimental petrology, in attempts to constrain the chemistry, mineralogy and temperature range of the lower mantle.

It appears that Mg-Fe silicate-perovskite plus magnesiowüstite could be stable to almost the mantle-core boundary. This assertion is made (eg. JEANLOZ & KNITTLE 1989) on the basis of new measurements of density (ϱ) and bulk modulus (K_o) and equations of state for high pressure and temperature minerals (Mg-Fe perovskites, KNITTLE & JEANLOZ 1987, WILLIAMS et al. 1989), Mg-Fe magnesiowüstites, RICHET et al. 1989) compared with seismological earth models (eg. PREM-model of DZIEWONSKI & ANDERSON 1981).

The new equation of state for $CaSiO_3$-perovskite to 134 GPa presented by MAO et al. (1989) gives density (ϱ) and bulk modulus (K_o) close to that of $(Mg_{0.88}Fe_{0.12})SiO_3$-perovskite (KNITTLE & JEANLOZ 1987) and also the PREM-model (DZIEWONSKI & ANDERSON 1981) for the lower mantle. Thus a separate $CaSiO_3$-perovskite phase will not be identifiable in seismic studies from ϱ-K_o constraints. In any case it is likely that available Ca, Al and Ti will enter the Mg-Fe silicate-perovskite (KATO et al. 1988) without forming a second Ca-rich silicate-perovskite phase.

From likely bounds on the composition of the upper mantle (X_{Mg} = Mg/Mg + Fe ≥ 0.88) and temperatures in the lower mantle (T ≥ 2,000 K), JEANLOZ & KNITTLE (1989) proposed that the mineral assemblages in the depth range 1,000–2,000 km are more dense by at least 2.6 (± 1%) than the assemblages of the upper mantle. These calculations are disputed by CHOPELAS & BOEHLER (1989), who find no compelling reason for the lower and upper mantle to have different composition. BUKOWINSKI & WOLF (1990) conclude that still quite a range of lower mantle compositions is possible. This points again to the need for further in-situ high-temperature-pressure measurements of the densities of likely minerals with the expected composition.

Even though new results from high-pressure experimental petrology has verified that the γ-Sp = Pk + Mw phase change is a strong candidate for the 670 km seismic discontinuity, disparate results from high-pressure mineral physics still suggest that a uniform mantle composition is not indicated, and a chemical boundary layer, shallower than 1,000 km, appears to be necessary. Detailed studies of the additional seismic discontinuities in the lower mantle would therefore be of particular interest in interpreting deep dynamic processes (eg. REVENAUGH & JORDAN 1989, YOUNG & LAY 1987).

Although TSUCHIDA & YAGI (1989) have experimentally produced a new high pressure polymorph of SiO_2 with the $CaCl_2$ structure, stable at higher pressures than stishovite, this phase is not likely to be a major mineral in the mantle. JEANLOZ (1989a) speculates that this phase could become important in the D″ layer of the lowermost mantle, if ultra high-pressure liquid iron from the outer core reacts vigorously with crystalline perovskite and magnesiowüstite (eg. KNITTLE & JEANLOZ 1989).

Magnetic field, seismic tomography and mantle dynamics

Particularly current in mantle research are the ways in which the various studies outlined above are being integrated in more precise attempts to quantify the dynamics of the planetary interior. Even processes deep within the mantle can be manifest in the geoid-the figure of the Earth at the surface (HAGER 1984, HAGER et al. 1985, RICHARDS & HAGER 1989, HAGER & CLAYTON 1989).

Studies of variations in the Earth's magnetic field in historical (BLOXHAM & GUBBINS 1987, GUBBINS & BLOXHAM 1987) as well as ancient times (LOPER & MCCARTNEY 1986) are being correlated with observations of mapped lateral and vertical regions of relatively faster-slower velocities, obtained from seismic tomography (DZIEWONSKI & WOODHOUSE 1987). Of particular interest are studies of the D″ region, the chemical/thermal boundary layer just above the core-mantle boundary (JEANLOZ & RICHTER 1979, MORELLI & DZIEWONSKI 1987, YOUNG & LAY 1987). Further studies might show the extent to which material transfer of iron (metal or oxide?) from the core to lower silicate mantle occurs, in addition to heat transfer (STEVENSON 1981, ELLSWORTH et al. 1985, KNITTLE & JEANLOZ 1989).

Lateral and vertical temperature variation in a dynamic mantle

By interpreting the fast-slow seismic velocity regions as relatively colder-hotter locations in a dynamic mantle, the possible heterogeneities are being examined as to whether they more likely represent chemical variation (HOFFMAN & MCKENZIE 1985, ANDERSON 1989, ANDERSON 1989a), seismic anisotropy (SILVER & CHAN 1988, MONTAGNER & ANDERSON 1989), or thermal/advective domains (BINA & KUMAZAWA, in press).

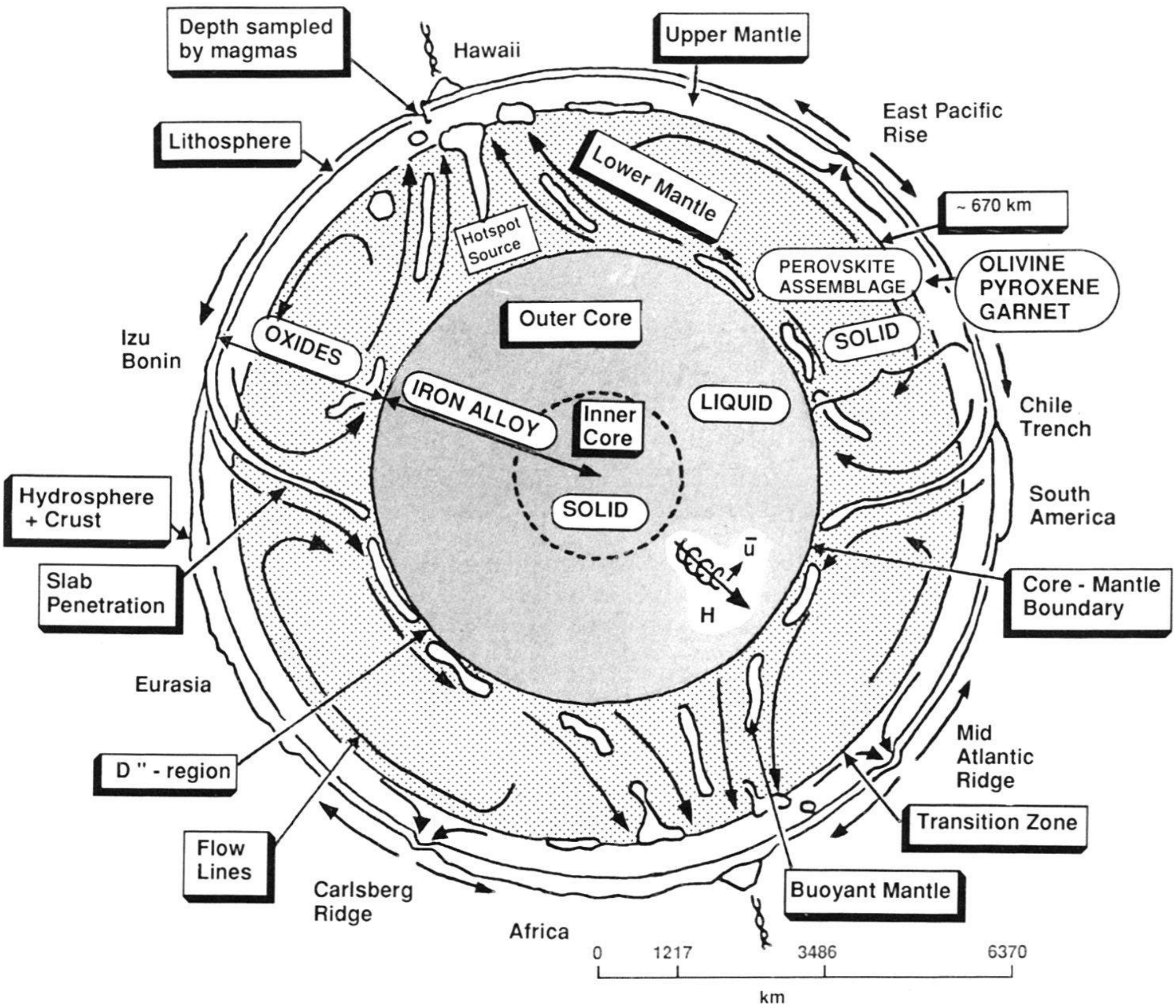

Fig. 1. Schematic sketch of the dynamic Earth's mantle that shows both slab-penetration into the lower-mantle and a 1.7 Ga residence-time for material involved in the plate-tectonic cycle (modified from SILVER et al. 1988, Fig. 12, p. 525; with additions from Fig. 1 of KERR 1990 and Fig 1 of JEANLOZ, 1989a). The 2% density difference between subducted material that has penetrated the 670 km discontinuity, would cause it to rise buoyantly from the core-mantle boundary. Deeply subducted buoyant mantle material mixed with ambient mantle can only be subsequently sampled at ocean ridges if the hot rising jets from the lower mantle can traverse the upper mantle. The flow-lines show a generous degree of leaky tow-layer convection. If subducted slabs do not penetrate the 670 km seismic discontinuity then the present interior may contain at least three major separately-convecting systems (upper mantle, lower mantle, outer core). It is to be expected that heat-transfer occurs across the D″-region and across the mantle transition-zone, but the extent of mass-transfer is not easy to assess. Any "buoyant mantle material" originating in the D″-region must represent a deep hot-spot source. If the density contrast of such rising material is lost at the 670 km discontinuity the plume cannot easily cross the mantle transition zone. Much current evidence supports a more "conservative" view of present mantle convection, where material is largely conserved within three-major convecting systems. In which case some of the diagramatics shown between 670 km and the core-mantle boundary would then be displaced to shallower than 670 km. In the early stages of Earth evolution, convection could have been mantle-wide, until secular cooling through the appropriate solidii locked the mineralogy (and hence chemistry) of the lower and upper mantle. It is indeed a challenge to deduce these early events from observations on ancient rocks at the present surface.

Advective plumes rising from the core-mantle boundary may normally only be involved in the lower-mantle part of a two-layer convection system. However, their upward leakage across the transition region (see OLSON 1984) into the upper mantle to form hot-spots (eg. RICHARDS et al. 1989) may temporarily upset two-layer mantle convection (labelled "one-and-a-half layer" convection by NATAF 1989). Presumably if this occurs, it does so coupled with deep subduction of oceanic slabs through the apparent but imperfect chemical boundary layer near 670 km (see schematics in Fig. 1). Even if many slabs do pond at the 670 km discontinuity (because according to RINGWOOD 1989, density contrasts between slab and mantle have apparently disappeared by this depth) they could exert a "cold-finger" effect on lower mantle convection.

It is not at all clear which feature is active (i.e. slab-penetration or the plume-flow) in controlling the passive response of the other. Presumably the thermal contrast between old slabs and mantle will disappear as the accumulated material heats up, so that only young subducted slabs should influence lower mantle convection.

By way of contrast, MORELLI & DZIEWONSKI's (1987) seismic tomographic observations that depression of the core-mantle boundary appears to be associated with regions of present-day subduction, has been taken to indicate that convection should be regarded as mantle wide (see for example SILVER et al. 1988).

New studies in tomographic seismology in the transition region of the mantle (between the 400 and 670 km seismic discontinuities), might ultimately reveal the conditions that lead to disruption of two-layer convection – causing transient or local whole-mantle convection. Such disruption could have catastrophic consequence that even could be manifest at the Earth's surface through intense magmatic activity (eg. flood basalts) over a geologically short time period.

Primordial mantle stratification and current mantle heterogeneitis

The geochemical evidence referred to above, suggests ancient depletion of the mantle source for mid-ocean ridge basalts (MORB). By analogy with the "magma-ocean" proposed for early lunar evolution (eg. HOFMEISTER 1983), a terrestrial mantle source enriched in KREEP (potassium, rare-earth-elements, phosphorus) could have developed through crystal fractionation in major early terrestrial differentiation events (ANDERSON 1982, OHTANI 1985, KATO et al. 1988, RIDLEY & KRAMERS 1990). Such interpretations imply that large parts of the mantle are not sampled through current magma genesis. This could suggest that a large part of the mantle is not influenced by recent plate-tectonic processes, and that the mantle exhibits significant chemical heterogeneity (see discussion among HOFMANN & WHITE 1982, HOFFMAN & MCKENZIE 1985, ALLEGRE et al. 1987, HART & ZINDLER 1989).

Continental roots, lithosphere rheology and the other seismic discontinuities

The lithospheric plates themselves can considerably influence the style of mantle convection, through the break-up of supercontinents above plumes and their reamalgamation above subduction zones (eg. JACOBY & SCHMELING 1982, DAVIES 1988, GURNIS 1988). Very deep roots to continental lithosphere (to perhaps 400 km, LERNER-LAM & JORDAN 1987, LAY 1988, JORDAN 1989) can conceivably further influence the form of mantle convection, by diverting advective plumes rising from the deeper mantle (extrapolating the arguments of POLLACK 1986).

The rheological role of the lithosphere in influencing magma ascent needs also to be further assessed before geochemical inferences on the depth and extent of mantle reservoirs for magmas, can be simply linked to the convection system (see the additional comments by KARATO 1981, DAVIES 1989).

More detailed studies worldwide of the 670 km and the other poorly defined seismic discontinuities (see summary by ANDERSON 1989b, 49–60) to see how widespread, deep, wide and sharp these horizons are, would certainly help us to decide whether they could represent chemical boundary layers and therefore their significance in the whole, versus two-layered, mantle convection story. Together with appropriate high-pressure experimental petrology (following on from the work of HERZBERG 1983, BINA & WOOD 1984, ITO et al. 1984, IRIFUNE et al. 1986, IRIFUNE & RINGWOOD 1987a, IRIFUNE & RINGWOOD 1987, GASPARIK 1989), such new seismological information will certainly help to clarify further aspects of the coupling between chemistry and dynamics in the mantle and constrain three-dimensional spherical models of convection in the mantle (eg. BERCOVICI et al. 1989).

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