Structure of the Core-Mantle Transition Zone:

A Chemical and Thermal Boundary Layer

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A remarkable diversity of geophysical techniques is being used to probe the transition zone between the outer core and the lower mantle. This inaccessible region, 2900 km below the Earth's surface, is now recognized to profoundly influence the style of mantle convection, thermal and chemical plume formation, secular variation, and possibly reversals of the magnetic field, core-mantle exchanges of angular momentum, long-wavelength gravitational variations, and chemical evolution of the Earth. Establishing the thermal and chemical structure of the lowermost mantle and outermost core is critical to our understanding of the dynamic processes near this transition zone, and progress is now accelerating as a result of an interdisciplinary approach. Recent contributions from seismology, mineral physics, geomagnetism, and geodynamics are synthesized in this article, and a model with a combined thermal and chemical boundary layer at the core-mantle boundary is proposed. The recent formation of the IUGG and AGU committees for SEDI (Studies of the Earth's Deep Interior) is facilitating communication in this and related interdisciplinary efforts to understand how the interior of the planet works.

Introduction

The core-mantle boundary (CMB) separates dynamic systems with remarkable contrasts in composition and material properties (Table 1), comparable in magnitude to variations in properties across the surface of the solid Earth. A natural consequence of this pronounced stratification is the development of thermal and chemical boundary layers adjacent to these interfaces, which thereby constitute the major transition zones in the planet. The importance of the surface and CMB boundary layers for both dynamic and chemical fractionation processes throughout the history of the Earth has long been appreciated, but only recently has a concerted effort been made to study the boundary layer at the base of the mantle. Whereas the near-surface regime is accessible for a broad range of analyses, all investigations of the core-mantle transition zone must be conducted using geophysical remote sensing procedures. As a result, progress in characterizing this region has been slow and controversial; however, recent advances in several geophysical disciplines have accelerated our understanding of and interest in the processes occurring near the major internal discontinuity within the Earth.

The most direct constraints on the properties of the core-mantle transition zone are provided by seismology, mineral physics, geomagnetism, and geodynamics. Seismological contributions have the longest history and continue to provide critical information about the variation in properties within the transition zone. New technological developments in mineral physics allow laboratory experiments to now be conducted at pressure and temperature conditions appropriate for the CMB. These experiments have provided unprecedented constraints on the temperature, composition, and material properties of the region. Recent inversions for the magnetic field at the CMB have unveiled detailed spatial characteristics of the geomagnetic secular variation and the associated inferred core flow regime, which appear to be coupled to properties on the mantle side of the transition zone. In addition, geodynamic constraints on flow in the mantle induced by seismically detected heterogeneity, analyses of long-wavelength components of the geoid and fluctuations in the length of day, and calculations of boundary layer instabilities, plume formation, and dynamic topography, are all impacting the interpretation of the properties of the core-mantle transition zone.

The lowermost mantle was recognized to have anomalous seismic properties as early as the 1930s when the first whole Earth seismic models were produced. On the basis of reduced velocity gradients and increased lateral variability relative to the overlying homogeneous mantle, the 200- to 300-km thick zone at the base of the mantle was designated the D″ region by *Bullen* [1949]. The subsequent 40 years of analysis has provided refined characterizations of the seismic properties of the D″ region, but there is still ongoing debate over the relative importance of thermal versus chemical inhomogeneity. The idea that a major thermal boundary layer is responsible for the anomalous behavior is pervasive in the literature [e.g., *Jones*, 1977; *Jeanloz and Richter*, 1979; *Doornbos et al.*, 1986], but there has recently been increased consideration of possible chemical heterogeneity in the light of various seismic and mineral physics results. This article will highlight some of the recent developments in various geophysical fields that are revolutionizing our understanding of the core-mantle transition zone.

New Seismological Constraints on the Core-Mantle Transition Zone

The D″ region is clearly anomalous even in radially symmetric models of the deep Earth's material properties, such as the Preliminary Reference Earth Model of *Dziewonski and Anderson* [1981]. The decreased P and S wave velocity gradients above the CMB in this model have been used to infer the existence of a thermal boundary layer with an 800° temperature contrast [*Stacey and Loper*, 1983], while even stronger decreases in velocity gradients proposed on the basis of diffracted wave analyses almost defy a reasonable thermal explanation [*Doornbos et al.*, 1986]. But it must be recognized that a great diversity of seismic models has been proposed for the D″ region (as reviewed by *Young and Lay* [1987*a*]), with there being no consensus on what constitutes even a best "average" model. In the last 15 years the recognition that scattering from lateral velocity heterogeneity is particularly pronounced in D″ [e.g., *Haddon*, 1982; *Bataille et al.*, 1988] has profoundly altered seismological approaches to analyzing the region. Research in the last 5 years has concentrated on resolving the lateral heterogeneity spectrum of the region at scales ranging from 10^1 to 10^4 km, coupled with detailed investigations of localized regions to provide enhanced resolution of velocity gradients and possible stratification.

Long-wavelength variations in the seismic properties of the D″ region have been determined using tomographic inversion of large data sets of P wave and S wave travel times and waveforms. Figure 1 displays the perturbations in P velocity structure near the base of the mantle obtained by *Dziewonski* [1984] in an analysis of 500,000 travel time residuals. The low-order (degrees 2–6) spherical harmonic components of the heterogeneity have 1.0–1.5% velocity variations, which are 3–4

Cover. Photographs of Mars in six different wavelengths from 0.4 to 0.8 μm, taken during opposition in August and September 1988, when the planet was only 59 × 10^6 km from Earth. High-resolution imaging and spectroscopy studies of Mars done at the University of Hawaii are described in the news story "Mars During the 1988 Opposition" on page 51.

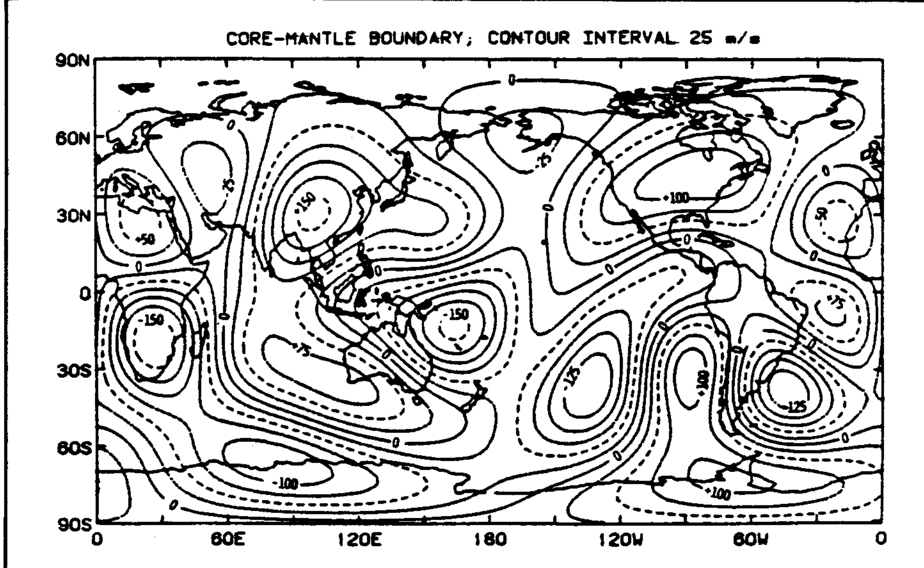

Fig. 1. Map of *P* velocity anomalies at the core-mantle boundary for spherical harmonics up to degree and order 6 obtained by *Dziewonski* [1984]. Positive perturbations indicate faster than average material.

times stronger than in the central mantle. There is, however, some spatial continuity between regions of faster than average material in D″ and fast regions in the overlying mantle, located roughly below the circum-Pacific margins. Other global *P* wave travel time inversions have been performed [*Clayton and Comer,* 1983; *Hager and Clayton,* 1988], which have some similarity in long-wavelength characteristics with the model in Figure 1, but poor agreement for shorter wavelengths. For example, the low-velocity region below Africa in Figure 1 is a dominant feature in the other *P* wave models. The sampling of the deep mantle is not uniform, so some of the discrepancies between the models are artifacts of the spherical harmonic expansions. The truncated expansions of the heterogeneity also provide strong smoothing of what may be smaller-scale, larger-magnitude velocity heterogeneities.

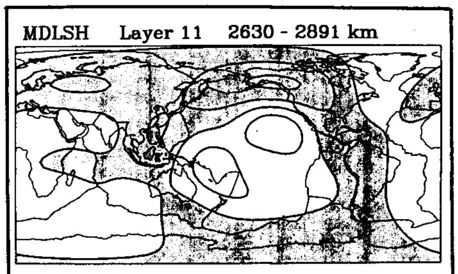

Fig. 2. Map of long wavelength *S* velocity anomalies in the D″ region obtained by *Tanimoto* [1988]. The dark areas are faster than average (PREM), and the contour inverval is 0.5%.

Coherent large-scale variations are also apparent in shear velocity models obtained by waveform modeling of digitally recorded *S* waves, as shown in Figure 2, from *Tanimoto* [1988]. This long-wavelength model exhibits a pronounced ring of high shear velocities with several percent velocity perturbations in D″ beneath the circum-Pacific, as does a model obtained by *Woodhouse and Dziewonski* [1987] using a similar procedure. The continuity of these high-velocity structures upward into the mantle, along with strong correlations between lower mantle low-velocity heterogeneity patterns for degrees 2 and 3 and the long-wavelength components of the hot spot distribution at the surface, are suggestive of thermally induced variations in a complex system of large-scale convection in the lower mantle [e.g., *Hager et al.,* 1985; *Hager and Clayton,* 1988; *Silver et al.,* 1988].

Much smaller-scale heterogeneity in D″ has been inferred from a variety of scattered core phases (reviewed by *Bataille et al.* [1988]). An analysis of scattered PKP precursors by *Bataille and Flatté* [1988] indicates that for wavelengths of 10–70 km the wavelength spectrum of *P* velocity inhomogeneity is best represented by a power law with index 6. Assuming a volumetric scattering mechanism in a 200-km thick layer, about 0.5% *P* velocity variations are needed for these short-scale lengths, which could be produced by thermal fluctuations of about 700 K. Alternatively, 280 m rms of topography on the CMB with similar scale lengths can account for the PKP precursor amplitude behavior, as well as backscattered precursors to PKKP [*Chang and Cleary,* 1981; *Doornbos,* 1988].

The existence of longer-wavelength topography on the CMB has also been suggested by analysis of PKP and PcP travel times. Figure 3, from *Morelli and Dziewonski* [1987], shows the results of an inversion indicating more than 10 km of relief with 3000–6000 km scale lengths. Note that depressed regions tend to correlate with zones of higher seismic velocities in D″ in Figures 1 and 2, which sug-

TABLE 1. Contrasts in Material Properties Across the Core-Mantle Transition Zone

Property	Outer Core	Lower Mantle
Composition	Fe + 10% (O,S,Si,C)	$Mg_{0.9}Fe_{0.1}SiO_3$ in perovskite structure $+(Mg,Fe)O+CaSiO_3$
State	molten alloy	subsolidus
Temperature	3800 K–4700 K	2600 K–3100 K
Flow Velocity	$O(10^1)$ km/a	$O(10^{-4})$ km/a
Viscosity	$O(10^{-2}$–$10^3)$ Pa s	10^{22}–10^{23} Pa s
Density	9.90×10^3 kg/m^3	5.57×10^3 kg/m^3
Rigidity	$O(0?)$ Pa	2.911×10^{11} Pa
Electrical Conductivity	10^5–10^6 S/m	10^{-2}–10^2 S/m
Incompressibility	6.35×10^{11} Pa	6.85×10^{11} Pa

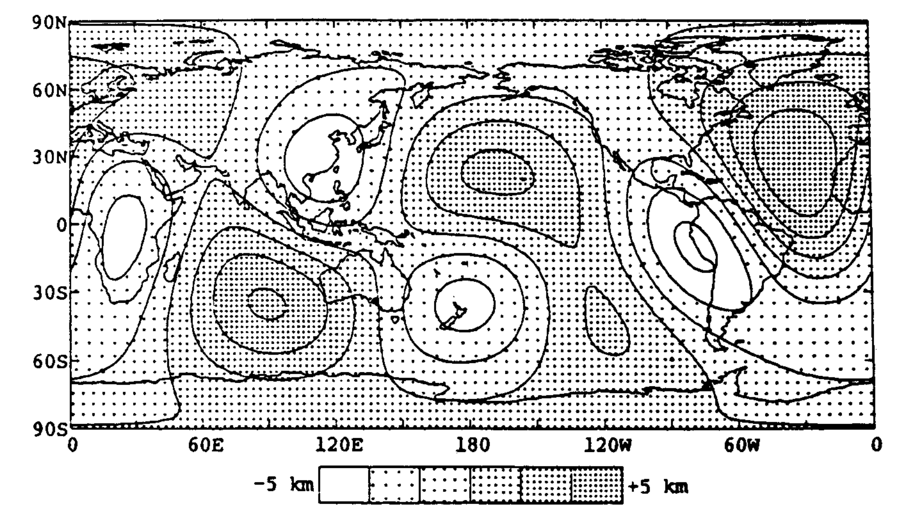

Fig. 3. Core-mantle boundary topography obtained by *Morelli and Dziewonski* [1987] from analysis of PKPbc and PcP travel times.

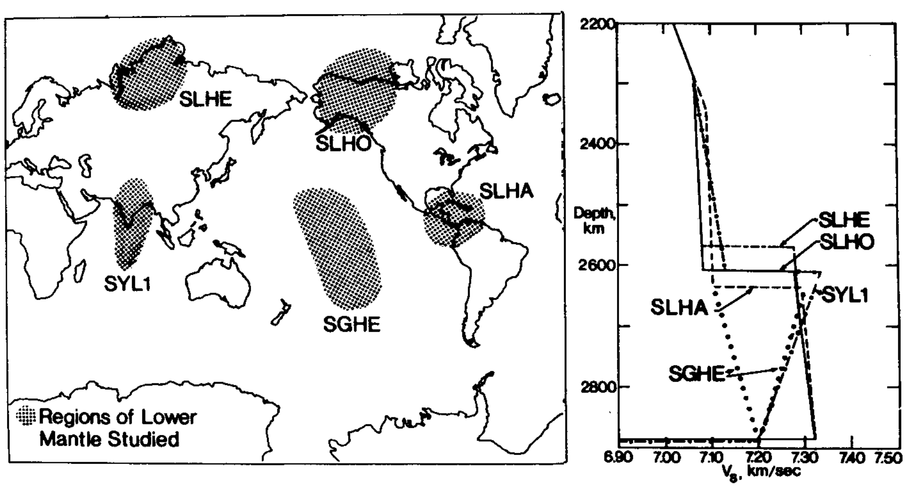

Fig. 4. Detailed *S* velocity models obtained for various localized regions of D″ by waveform modeling of body waves. SLHO, SLHA, and SLHE are from *Lay and Helmberger* [1983]; SYL1 is from *Young and Lay* [1987*b*], and SGHE is from *Garnero et al.* [1988]. The latter model involves strong lateral gradients in shear velocity in the region below the central Pacific.

gests that the topography is dynamically supported by downwelling of cool mantle material. Qualitatively similar results have been reported by *Gudmundsson et al.* [1986] for a different model parameterization. While the joint inversion of PKP and PcP is particularly powerful for resolving boundary topography, other inversions of PKP and PKKP travel times have resulted in incompatible models of heterogeneity located on either the mantle or the core side of the boundary [*Creager and Jordan,* 1986; *Doornbos and Hilton,* 1988], so the assessment of these models is still undergoing scrutiny.

The resolution of the lateral heterogeneity and radial structure of D″ is also advancing for intermediate scale lengths of 100–1000 km. Using waveform modeling procedures and data sets selectively sampling localized regions of the lower mantle, several investigators have obtained provocative results. Figure 4 summarizes models of the shear velocity structure in D″ obtained by *Lay and Helmberger* [1983], *Young and Lay* [1987*b*], and *Garnero et al.* [1988] for isolated patches of D″. All of the regions sampled other than below the Central Pacific are observed to have precursors to the core reflection, ScS, which have been modeled as reflections from a seismic discontinuity at the top of the D″ layer. Comparison with Figure 2 indicates that these regions correspond to areas with large-scale high-velocity perturbations, while the patch below the Pacific is in the lowest-velocity area. It is unlikely that the discontinuities in the shear velocity structure can be accounted for by thermal boundary layer properties, leading to the suggestion that localized compositional stratification or possibly a phase change may be responsible. This "layering" appears to vary laterally given the lack of evidence for a strong discontinuity under the Pacific in several studies [*Schlittenhardt et al.,* 1985; *Garnero et al.,* 1988; *Revenaugh and Jordan,* 1988].

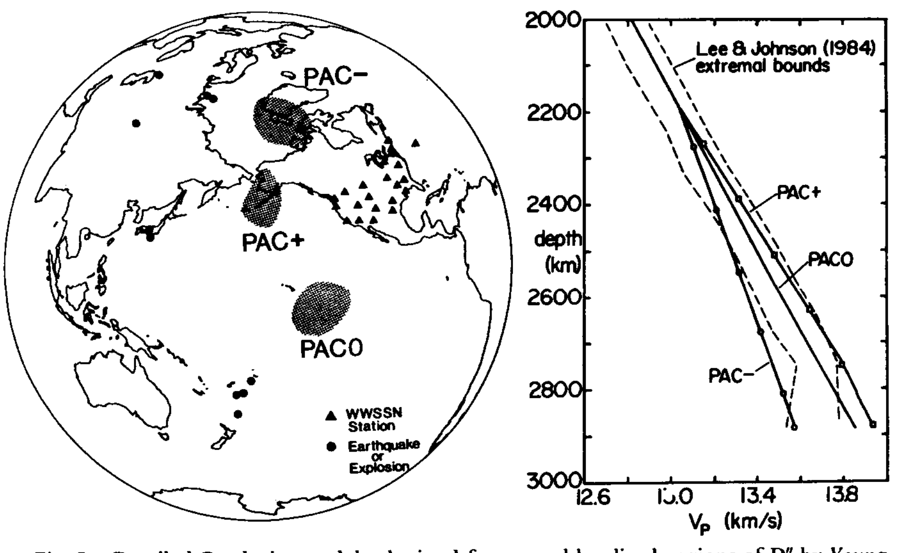

Fig. 5. Detailed *P* velocity models obtained for several localized regions of D″ by *Young and Lay* [1988], by modeling short-period *P* waves near the onset of the core shadow zone boundary.

This does not preclude the possibility of a phase change given that an isobaric phase change could still be induced by strong lateral temperature gradients in D″ [e.g., *Anderson,* 1987*a*].

Interpretation of the seismic data is complicated by the possibility that the precursors are actually scattered arrivals from lateral heterogeneity in D″ [*Haddon and Buchbinder,* 1987]; however, the latter mechanism appears to require extensive low-velocity heterogeneity which is inconsistent with the results of the large-scale tomographic inversions. Current seismic procedures and data sets are insufficient to uniquely resolve this question, but deployment of dense networks of broadband seismic sensors should improve the model resolution.

Similar detailed analysis of *P* waves sampling localized regions have indicated the presence of *P* velocity discontinuities at the top of D″ [*Wright et al.,* 1985; *Baumgardt,* 1988], as well as the absence of such structure [*Schlittenhardt,* 1986]. While these results are still very controversial, a recent analysis of short-period diffracted phases sampling localized regions [*Young and Lay,* 1988] has provided clear evidence of strong lateral gradients in average *P* velocity structure in D″, with the results being shown in Figure 5. These models confirm the qualitative nature of the large-scale tomographic inversions, with 1.5% lateral variations over 10^3- to 10^4-km scale lengths, but also suggest that the anomalous region is thicker than conventional models for the D″ layer, as well as having less pronounced decreases in velocity gradient than have been obtained in travel time and long-period diffracted wave studies.

Thus seismology is providing a spatial characterization of the averaged and detailed elastic properties of the mantle side of the core-mantle transition zone, as well as evidence for topography on the interface. But it is necessary to bring in constraints from mineral physics to address the basic issue of apportioning the chemical and thermal interpretations of these variations.

New Mineral Physics Constraints on the Core-Mantle Transition Zone

Experiments conducted in the laser-heated diamond anvil cell have recently provided new constraints on the material properties of the dominant lower-mantle mineral phase, silicate perovskite, as well as melting relations in the iron-oxygen and iron-sulfur systems relevant to the core alloy. These experiments have also indicated that chemical reactions between the mantle and the core may be occurring, leading to the development of a chemically distinct reaction zone in D″.

Recent diamond anvil results indicate that $Mg_{0.9}Fe_{0.1}SiO_3$ in the perovskite structure is stable to pressures of 1.3 mbar and 4000 K [*Knittle and Jeanloz,* 1987]. Since all of the major components of proposed upper mantle compositions will undergo a transformation to this phase (in combination with magnesiowustite), silicate perovskite is believed to be the dominant phase in the lower mantle, although the precise relative abundance of Mg and Fe and the amount of $CaSiO_3$, Al_2O_3, and (Mg,Fe)O that may also be present is not well resolved. Measurements of the melting point of silicate perovskite thus place important bounds on the mantle geotherm. The experimental work indicates that the melting point increases from 3000 K to over 3800 K over the pressure range 0.3–1.3 mbar, which spans the lower mantle [*Heinz and Jeanloz,* 1987; *Ahrens and Jeanloz,* 1988]. If there is a eutectic in the perovskite-magnesiowustite system for deep mantle conditions, the solidus may be significantly lower. Recent estimates of mean lower mantle adiabats (Figure 6) range from 2600 K to 3100 K [*Jeanloz and Morris,* 1986], so that any strong temperature increase in the D″ region may approach the solidus, leading to the possibility that partial melting contributes to the anomalous characteristics of the region. The absolute temperatures in the lower mantle have great uncertainty because of the unresolved question of whether there is a thermal boundary layer at the 670-km discontinuity. Such a boundary layer would develop for a chemically stratified Earth with sufficient density contrast at the boundary to prevent significant mass transport across it.

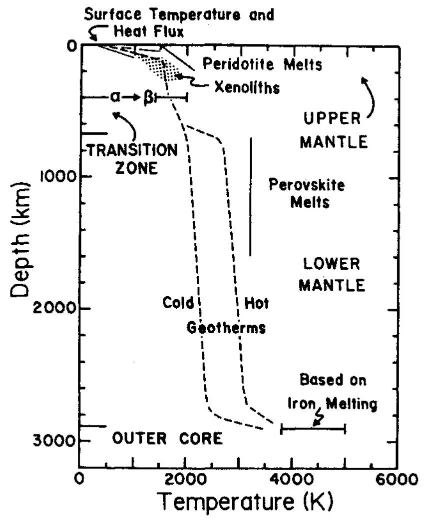

Fig. 6. Average mantle geotherms from the review paper by *Jeanloz and Morris* [1986]. The melting temperature of perovskite is now believed to increase with depth to about 3800° near the core-mantle boundary. A strong thermal boundary layer in D″ appears to be required by the estimates of outermost core temperatures of greater than 3800°.

Other material properties of the silicate perovskite phase are being resolved by experiments at high pressures and temperatures. The thermal expansion coefficient of perovskite has been found to have an unexpectedly high value of 4.0×10^{-5} K^{-1} at zero pressure and temperatures greater than 1000 K [*Knittle et al.,* 1986], which implies that candidate upper mantle compositions will have a 2.6 +/- 1% density deficit relative to the measured value for the lower mantle upon undergoing the perovskite phase change [*Jeanloz and Knittle,* 1988]. This lends support to the long history of arguments for a compositional change across the 670-km discontinuity [see *Ringwood and Irifune,* 1988; *Anderson and Bass,* 1986], and has many implications for the dynamics of the lower mantle and the role played by the core-mantle transition zone; ongoing work is seeking to confirm this result.

High-pressure electrical conductivity measurements on perovskite have yielded very low estimates of 10^{-2} S/m [*Li and Jeanloz,* 1987] for mid-mantle conditions. This estimate is 3–4 orders of magnitude lower than the values obtained by analysis of geomagnetic secular variation. These experiments are quite controversial; for example, it is possible that perovskite is an ionic conductor, with a higher net conductivity than inferred from electron transport. However, even if the central mantle is in fact such an effective insulator, the D″ region may serve to electromagnetically couple the mantle and core. This possibility is supported by recent experiments demonstrating that molten Fe, FeO, and FeS can all react vigorously with silicates at CMB conditions [*Knittle and Jeanloz,* 1986; *Williams et al.,* 1987*b*], which could result in iron enrichment of the D″ region and a strong increase (by perhaps 10^4 S/m) in electrical conductivity of this layer. However, given the low diffusion coefficients involved in such iron enrichment, accumulation of a chemically distinct zone more than a few hundred meters thick requires that a dynamic mechanism be sweeping away the reaction zone and exposing fresh mantle material to the core. Either small-scale convective eddies or a mechanism such as capillary action [*Stevenson,* 1988], involving dense liquid migration along grain boundaries would be required to develop a significant volume of iron enriched material.

Vigorous research continues on identifying the light alloying component of the outer core. Recent results have supported the long-standing suggestion that both sulfur [*Ahrens and Jeanloz,* 1987] and oxygen [*Knittle and Jeanloz,* 1986] are plausible light alloying components; however, these two candidate components appear to have markedly different effects on the alloy melting temperature, and hence on the estimated outer core temperature. At high pressures, several experiments indicate that oxygen increases the melting temperature of an Fe-FeO system relative to pure Fe, while the presence of sulfur in an Fe-FeS system depresses the melting point from that of pure Fe by about 400 –800 K [*Williams et al.,* 1987*b*; *Svendsen et al.,* 1988]. There is continuing controversy over the actual eutectic compositions at core conditions for various alloys, but combining these results with the recent estimate of 4800 +/- 200 K as the melting temperature of pure iron at the CMB [*Bass et al.,* 1987; *Williams et al.,* 1987*a*; *Svendsen et al.,* 1988], it appears that the outermost core temperature is at least 3800 K (Figure 6), while other estimates of the minimum outer core temperature are as high as 4400 K [*Ahrens and Hager,* 1987]. These high outer core temperature estimates require a temperature increase of at least 700 K across a thermal boundary layer in D″. Temperature dependence of viscosity in the deep mantle would make such a hot thermal boundary layer dynamically unstable unless there is a stabilizing compositional change in the region, and the material in D″ would approach the mantle solidus. The thermal implications of other light alloying components and mixtures of alloys are yet to be worked out, with some preliminary results indicating that even small amounts of sulfur in an Fe-FeO system will dramatically depress the melting temperature [*Williams et al.,* 1987*b*].

The high-pressure experimental results and analysis of the seismic tomography models are leading to an improved understanding of the deep mantle equation of state [*Anderson,* 1986; 1988]. This is critical to our ability to interpret the seismic velocity heterogeneity of D″ in terms of temperature versus chemical variations. Temperature is less effective in altering density and seismic velocity at high pressures than was assumed in many of the early interpretations [e.g., *Stacey and Loper,* 1983], which increases the difficulties of interpreting the D″ region solely as a thermal boundary layer. In addition, the recent estimates of temperature dependence indicate that a thermal boundary layer would be thicker than in early models. Application of this new understanding to the current seismic models in Figures 1–5 is now in progress.

New Geomagnetic Constraints on the Core-Mantle Transition Zone

While inversions of geophysical data for flow in the outer core continue to be controversial and inconsistent, images of the magnetic field at the CMB [*Bloxham and Gubbins,* 1985] do suggest that the deep mantle plays a major role in controlling the secular variation of the magnetic field. On the basis of stationarity of some magnetic features for several centuries, and rapid evolution of others, as well as a correspondence between the respective regions and tomographic images of deep mantle velocity heterogeneity, *Bloxham and Gubbins* [1985, 1987] suggest that the mantle controls the outer core flow by a thermal coupling mechanism. Regions of upwelling material in the core are associated with seismically slow, presumably hot regions in D″, and core downwellings are associated with seismically fast (cold) regions in the mantle. Thermal coupling of this type is not a new idea [*Jones,* 1977; *Ruff and Anderson,* 1980], but only recently have the separate research efforts in seismology and geomagnetism produced global models which can be directly compared to test this idea. The thermal coupling mechanism is basically a variable heat flux boundary condition on the core convection system, with the CMB itself remaining essentially isothermal due to the rapid flow velocities in the core [*Davies and Gurnis,* 1986; Table 1]. Cold areas in the mantle should have higher heat flux out of the core; a situation for which classic Rayleigh/Bernard convection would generally predict upwellings in the core. However, *King and Hager* [1987] have found that for moderate Rayleigh numbers and highly variable heat flux, the Bloxham and Gubbins hypothesis is still viable. The depth to which this mechanism can affect core flow is controversial [*Jones,* 1977; *Bloxham and Gubbins,* 1987].

Another possible mechanism by which the mantle may influence the geodynamo and its secular variations is the combined mechanical and thermal effect of CMB topography. In the presence of topography, the isotherms will no longer coincide with gravitational equipotentials, so there will be both a lateral temperature gradient effect as well as mechanical interaction with the flow regime [*Gubbins and Richards,* 1986; *Bloxham and Gubbins,* 1987]. The presence of chemical heterogeneity with distinct thermal characteristics would complicate interpretation of the topographic mechanisms.

Gubbins [1987] has associated the pronounced low-velocity region in the lower mantle and D″ region below Africa in the seismic tomography models, with a "core spot" of rapidly evolving magnetic flux expulsion and westward migration of the magnetic field in the region. The orientation of the flux opposes the present dipole field, and its growth with time appears to be responsible for a secular decrease in the total field intensity, suggesting a possible mechanism by which thermal structure in the mantle may be responsible for magnetic reversals. *McFadden and Merrill* [1984], *Courtillot and Besse* [1987], and *Gubbins* [1988] have argued that the paleomagnetic reversal record is a consequence of the slowly evolving temperature variations in the mantle. Mantle thermal perturbations, perhaps associated with boundary layer instabilities in D″, may modulate the core flow regime, giving rise to periods of relative stability and rapid reversals. The intermittent convection in the mantle may require on the order of 150 Ma for the development of a thermal boundary layer, which will eventually become destabilized. The build up of the boundary layer will cause temporal variations in the heat flux boundary condition on the CMB which could perhaps explain the observed gradual increase in reversal frequency since the Cretaceous. This scenario of mantle-core thermal and mechanical coupling emphasizes the importance of geodynamical investigations of the core-mantle transition zone.

New Geodynamical Constraints on the Core-Mantle Transition Zone

A wide range of geodynamical calculations and observations bear upon the processes occurring at the base of the mantle. Large-scale geodetic observations of the geoid, the external gravitational potential, and fluctuations in the Earth's rotation provide important bounds on the deep Earth structure. As soon as the first aspherical Earth models from seismology revealed the existence of significant long-wavelength lateral heterogeneity in the lower mantle, calculations were performed to appraise the effects on the geoid and the expected dynamic topography on the CMB that would be induced by viscous flow in the mantle. *Hager et al.* [1985] calculated 3-km topography at the CMB for degree 2 and 3 wavelengths (5000 km), which is substantially smaller than and spatially unrelated to the seismic model of *Morelli and Dziewonski* [1987]. The existence of a low-viscosity zone in a hot thermal boundary layer or of a chemically distinct layer in D″ can reduce the expected dynamically supported topography on the boundary even further. The long-wavelength dynamic topography at the Earth's surface is not well constrained, but has been estimated as +/- 1 km [*Hager and Clayton*, 1988]. It is intuitively difficult to reconcile the seismic estimate of +/- 10 km of dynamic topography on the CMB, which has a larger density contrast than at the surface, with surface topography as small as 1 km. Efforts to better constrain the surface dynamic topography will thus give guidance in the interpretation of the CMB processes.

More direct constraints on the topography can be inferred from resonance in the Earth's forced nutations, which constrain the P_2^0 component of the CMB topography, satellite observations of the external gravitational component, which constrain the $P_2^{+/-1}$ components, and decade fluctuations in the Earth's rotation rate resulting from exchanges of angular momentum between the mantle and core [*Gwinn et al.*, 1986; *Speith et al.*, 1986; *Wahr*, 1988]. These geodynamical constraints require a 490 +/- 110 m peak-to-valley deviation of the CMB from its hydrostatic value, and long-wavelength topography of less than a kilometer, again at odds with the seismic modeling. It is possible that the effect of the topography is reduced by chemical heterogeneity on either side of the boundary, but there has not yet been a systematic search for such a core-side boundary layer.

The large temperature contrast across the CMB inferred from mineral physics has led to extensive numerical modeling of hot thermal boundary layer stability. The effects of temperature dependent viscosity and basal heating in the deep mantle will tend to result in boundary layer instability and formation of thermal plumes [*Yuen and Peltier*, 1980; *Loper and Stacey*, 1983; *Stacey and Loper*, 1983]. As long as the viscosity contrast across D″ is 10^4 or greater, plume formation can itself result in significant short-wavelength (20–50 km) dynamic topography on the boundary, which may account for the scattering of short-period PKP and PKKP seismic waves [*Olson et al.*, 1987]. *Loper and McCartney* [1986] have proposed that periodicity of such instabilities may account for some cyclical behavior of magnetic field reversals, by the basic thermal coupling mechanism described earlier.

If chemical heterogeneity exists in D″, it will substantially modify the dynamical behavior of the region, including plume instability, dynamic topography, and gross thermal structure. As a result, many recent numerical calculations of thermochemical convection have explored the effect of concentrations of chemical heterogeneity near the base of the mantle [*Davies and Gurnis*, 1986; *Christensen*, 1987; *Sleep*, 1988; *Hansen and Yuen*, 1988]. These calculations are also relevant to the broader geochemical issues of isotopic heterogeneity in the mantle and the nature of mantle mixing. While differing in detail, most of the models suggest that if heavy chemical dregs are located in D″, they will be swept into possibly laterally discontinuous aggregations by the action of the deep mantle convection system, with a tendency for the dregs to concentrate beneath the mantle upwellings. Continued replenishment of the chemical heterogeneity, perhaps by downwelling subduction products or by chemical reactions with the core, is needed for the chemical heterogeneity to survive the effects of entrainment in the mantle flow. The chemical boundary layer itself may either undergo small-scale convection [*Hansen and Yuen*, 1988; *Schubert et al.*, 1987] or it may be a stable conducting layer [*Ahrens and Hager*, 1987].

Geodynamical calculations are also quantifying the effects of depth dependent equation of state, compressibility, and three dimensionality of deep mantle flow [*Zhang and Yuen*, 1987, 1988; *Yuen et al.*, 1987; *Schubert*, 1988]. These calculations suggest that the thermal boundary layer structure may be quite different than in early models for D″, with a greater thickness and less induced dynamic topography. Both internal heating of the mantle and pressure dependence of thermal expansivity can inhibit boundary layer instabilities and plume formation. Many of the physical parameters that must be used in these numerical models are not yet well resolved, but considerable insight regarding the thermal and chemical processes in the core-mantle transition zone is being developed.

Chemical and Thermal Boundary Layer Model for the Core-Mantle Transition Zone

It is challenging, and perhaps premature, to distill a model for the core-mantle transition zone from the foregoing review of recent multidisciplinary results. Yet, it is useful in all fields to have a sufficiently complex strawman model with testable hypotheses and a unifying conceptual framework.

The evidence for a thermal boundary layer at the base of the mantle has grown relatively strong in the light of the mineral physics experiments. However, it is disturbing to see how hot the interior of Earth is getting in the latest models, both in the mantle and in the core, and many individuals have expressed their reservations about the proximity of the mantle temperatures to the perovskite solidus. This is in part due to the nature of mantle adiabats, which are laterally averaged temperature estimates, with several hundred degree fluctuations in upwelling and downwelling areas being quite plausible. There is also concern that the thermal boundary layer would be intrinsically so unstable that we would not expect to see a strong D″ region today if only thermal effects are responsible. Full exploration of the possible core alloy eutectic systems is needed before the temperature contrast across the transition zone is well established.

Evidence for chemical heterogeneity is provided by the seismic velocity discontinuity models, the strength of the lateral velocity gradients, and the experiments indicating chemical reactivity between molten iron and silicate perovskite. All of these areas are controversial, and other interpretations of each have been advanced. However, the plausibility of chemical heterogeneity is strongly bolstered by the very immensity of the density change between the core and the mantle, which is greater than that at the surface of the Earth. The development of laterally coherent or discontinuous density stratification on both sides of the core-mantle boundary would appear to be as natural a result of chemical fractionation in the planet as is the existence of continents [*Jordan and Creager*, 1987]. A chemical boundary layer could result from chemical reactions with the core, primordial stratification during inhomogeneous accretion, underplating by refractory materials expelled from the core, or subduction of dense, chemically fractionated material. Given the vigorous dynamics within the outer core, it appears that topography on the boundary is the best way to stabilize buoyant material, essentially in inverted lakes [*Anderson*, 1987*b*; *Hager*, 1987]. The presence of chemical heterogeneity will also tend to stabilize, at least locally, the mantle side boundary layer, perhaps even accommodating the temperature contrast by a double boundary layer system.

A candidate model, which is suggested by these considerations, is shown in Figure 7. Basically, the idea is that both large- and small-scale chemical heterogeneity in a variable chemical boundary layer (CBL) is embedded within a dynamic thermal boundary layer (TBL). The chemical heterogeneity may be ancient, dense refractory material or products of subducted lithosphere, with the density contrast of the material controlling the variation in thickness and continuity of the CBL. On the basis of the seismic discontinuity models, it appears that the CBL is most pronounced in areas of downwelling, rather than in upwellings as predicted by the convection calculations. Thermal instabilities in the form of plumes, as well as the larger-scale mantle circulation may reorganize and entrain the compositional heterogeneity. Both flow regimes will induce dynamic topography on the CMB with a wide spectrum of scale lengths, compatible with the seismic observations. However, the presence of chemical heterogeneity on both sides of the boundary can potentially reduce the dynamic interaction between the core and mantle arising from topography, allowing compatibility with the geodynamical constraints. A double thermal boundary layer will exist in regions with localized stratification, while in other areas, the temperatures in the boundary layer may approach the mantle solidus, with partial melting accounting for a component of the strong lateral variations in shear velocity. The associated lateral thermal gradients and topography will provide thermal and mechanical coupling between the mantle and core, thereby affecting the geodynamo. This visualization has many similarities to the combined thermal and chemical boundary layer at the surface of the Earth. Continued refinement of the whole spectrum of geophysical constraints will be needed to test and refine, or perhaps refute, this model. In particular, the possibility that all of the characteristics of the D″ region can instead be explained by an unstable thermal boundary layer alone must be thoroughly tested [*Schubert et al.*, 1987].

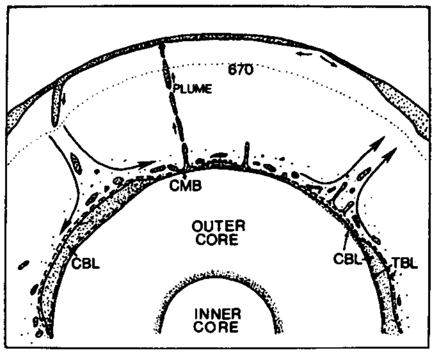

Fig. 7. A schematic model of the core-mantle transition zone which attempts to reconcile the constraints imposed by various geophysical measurements. A heterogeneous chemical boundary layer (CBL) is embedded in a thermal boundary layer. Large-scale mantle circulation transports chemical heterogeneity to the base of the mantle as well as returning some by entrainment. Thermal plumes caused by boundary layer instabilities ascend from the transition zone and disrupt the CBL. Topography on the core-mantle bounday (CMB) is induced by both the large- and small-scale dynamic systems. A core-side buoyant chemical boundary layer may aggregate in topographic highs. The lateral temperature gradients in the mantle may influence geomagnetic secular variations.

Several features of the model in Figure 7 can be tested by established techniques. Additional seismic modeling of localized regions is required to establish the global extent and variability of any seismic discontinuities in D″, along with resolving the ambiguity of the interpretation of the ScS precursors. The seismic evidence for CMB topography must be thoroughly examined to ensure that the results are not biased by projecting shallower heterogeneity onto the interface. The possibility of heterogeneity in the outermost core should be tested by detailed analysis of the SnKS suite of phases, which are most sensitive to this region of the core. Further analysis of plausible core alloy melting temperatures is critical to constraining the role of thermal boundary layers in D″, along with additional work on the mantle geotherm and solidus.

The interdisciplinary character of research on the core-mantle transition zone is summarized in Figure 8, which highlights the relevance of this region of the Earth for many geophysical fields. Even those disciplines which do not at present provide direct constraints on the region are influenced by the processes occurring there, as in the case for core-mantle chemical reactions undermining common geochemical assumptions about isotopic isolation of the core. The need for communication among the diverse research areas was the primary motivation for the creation of AGU and IUGG Committees for SEDI (Studies of the Earth's Deep Interior). Preliminary efforts to promote scientific interchange have taken place in the form of special issues of AGU publications (*Lay* [1986]: December *Geophysical Research Letters*) and AGU special sessions (Fall Meeting 1987; Spring Meeting, 1988).

The SEDI organizations are now holding biannual meetings, the first of which was held last summer in Blanes, Spain (the many presentations at that meeting stimulated this article). In addition, SEDI will continue to organize symposia such as the 1988 Fall AGU Meeting SEDI Symposium: "Lower Mantle Dynamics: Plumes, Slabs, the D″ Layer, and Interactions With the Core." It is hoped that the rapid rate of increase of our knowledge about the core-mantle transition zone and other fundamental regions of the deep Earth will be sustained by these interdisciplinary efforts.

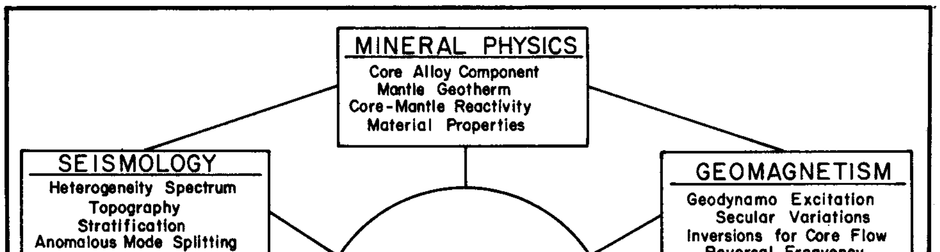

Fig. 8. A broad range of geophysical disciplines yield constraints on or are impacted by processes occurring at the core-mantle boundary. The interdisciplinary connections are highlighted in this chart. Communication between these fields is being fostered by the AGU and IUGG Committees for SEDI (Studies of the Earth's Deep Interior).

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