

## Unsuccessful initial search for a midmantle chemical boundary with seismic arrays

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**Abstract.** Compositional layering of the midmantle has been proposed to account for seismic and geochemical patterns [*van der Hilst and Karason, 1999*], and inferred radiogenic heat source concentrations [*Kellogg et al., 1999*]. Compositional layering would require thermal boundary layers both above and below an interface. We construct a minimal 1-D model of a mid-mantle boundary consistent with the observed nearly adiabatic compressional velocity structure [*Dziewonski and Anderson, 1981*] and the proposed high heat flow from the lower mantle [*Albarede and van der Hilst, 1999; Kellogg et al., 1999*]. Ray tracing and reflectivity synthetic seismograms show that a distinct triplication is predicted for short-period P waves. Although topography on a boundary would cause uncertainty in the strength and the range of the triplication, many clear observations would be expected. We examine data from the US West Coast regional networks in the most likely distance range of 60° to 70° for a 1770-km-depth boundary, and find no evidence for P wave triplications.

### 1. Introduction

Does the mantle contain chemically distinct upper and lower layers with comparable volumes? This debate has entertained geophysicists for many decades [*Davies, 1999; Schubert et al., in press*]. A variety of models are under consideration; a recent review [*Tackley, 2000*], for example, showed six possible configurations of primitive mantle, enriched recycled crust, and depleted MORB mantle.

The strongest evidence is for compositional variation in the lowermost mantle. Large local reductions in shear velocity, sometimes accompanied by increased compressional velocity [*Su and Dziewonski, 1997*], and possible coincidence of low velocities and high densities [*Ishii and Tromp, 1999*] are most naturally explained by variations in composition [*Tackley, 2000*].

A model with a compositional boundary between "upper" and "lower" mantles near 1700 km depth can explain several observations [*Kellogg et al., 1999*]. Slab penetration imaged by seismic tomography changes pattern near that depth [*Grand and van der Hilst, 1997; van der Hilst and Karason, 1999*]. Sequestration of primitive radiogenic material in such a lower mantle layer would provide an isolated reservoir for rocks with high  $^3\text{He}/^4\text{He}$  ratio and help explain the high observed heat flow through the surface of the Earth [*Hofmann,*

*1997; Kellogg et al., 1999*]. A horizontal barrier to vertical flow is necessary because otherwise, whole mantle convection is likely to homogenize mantle composition [*van Keken and Ballentine, 1999*].

This model is a modification of earlier suggestions that the mantle was layered at 660 km depth; however, layering at 660-km-depth has been rejected because downwellings from the upper mantle are now known to extend below 1000 km depth [*Grand and van der Hilst, 1997; Richards and Davies, 1992*]. The 660-km-depth had previously been chosen because there is a clear change in seismic velocities and density at this depth, which is now known to be explicable as a phase transition [*Stixrude, 1997*].

As is the case for the transition zone far above, the midmantle has been proposed as the site of phase transitions and dissociation of minerals, which complicates the search for chemical layering and interpretation of the local dynamics. Ferropiclasite, one of the bulk constituents of the lower mantle, has been proposed to dissociate into Fe- and Mg-rich phases that differ in density by 20% [*Dubrovinsky et al., 2000*]. Dissociation of (Mg,Fe)SiO<sub>3</sub>-perovskite in the lower mantle has also been proposed [*Mao et al., 1997*] but not universally accepted [*Serghiou et al., 1998*]. Such reactions might enable mantle segregation or appear as structures distorting seismic waves on their own.

The 1700-km-depth, in contrast to the 660-km-depth, has not been identified as having short-wavelength layered seismic structure (e.g., *Bina, 1991*), except for early studies suggesting very weak layering [*Johnson, 1969*]. However, isolated heterogeneity in the lower mantle has been inferred from scattered waves [*Castle and Creager, 1999; Kaneshima and Helffrich, 1998*]. This article estimates the seismic structure that would accompany a 1770-km-depth chemical boundary, and whether observable distortions to short-period seismic waves would result. A preliminary analysis indicates that the seismic distortion expected from a compositional boundary is not visible in our geographically-limited data. A similar conclusion has arisen from the unsuccessful search for a different seismic phase, transmitted S-to-P conversions at a midmantle boundary [*Castle and van der Hilst, submitted*].

### 2. Structure of a chemical boundary

Thermal boundary layers would have to exist both above and below a midmantle chemical interface, whether or not the interface is horizontal, in order to transport heat from the core and "lower" mantle into the "upper" mantle. These boundary layers would be of order 100 km thick and involve a temperature rise whose magnitude depends on the heat flux at

midmantle depth, a highly uncertain quantity. Midmantle heat flux is the sum of the heat flow from the core, the production from radiogenic elements in the "lower" mantle, and the rate of secular cooling of the "lower" mantle.

Some recent models [Kellogg *et al.*, 1999] would have the "lower" mantle contain a primordial concentration of heat producing elements, while other models [Davies, 1988; Sleep, 1990] would have the heat flux from the core be a small fraction of the Earth's surface heat flux. An upper bound to the midmantle heat flux can be obtained by assuming that all the Earth's heat flow ( $\sim 44$  TW) other than radiogenic heat flow from the continents ( $\sim 7.5$  TW [Schubert *et al.*, in press]) originates either in the "lower" mantle or core.

If 36.5 TW is transferred conductively across a 200-km-thick thermal boundary layer at 1770 km depth, and thermal conductivity  $k$  is assumed equal to  $6 \text{ W m}^{-1} \text{ K}^{-1}$  [Manga and Jeanloz, 1997], then the temperature rise  $\Delta T$  across the boundary layer would be about 18,000 K. Clearly, this is excessively large, and requires that only a small fraction (about 5%) of the heat flow from the mantle originate in the "lower" mantle, if  $\Delta T$  is to be of order  $10^3$  K. This illustrates a well-known thermal problem that arises if a primordial concentration of radioactive heat sources is present in the lower layer of a 2-layer mantle [Schubert and Spohn, 1981]. Because there are large uncertainties in the heat flow at midmantle depth, we assume a conservative value of  $\Delta T = 600$  K. This produces a  $0.1 \text{ km s}^{-1}$  peak seismic P-wave velocity anomaly [S. Karato, pers. comm., 2000], and corresponds to midmantle heat flow values much smaller than 36.5 TW. The heat flow is fairly well known, conductivity estimates range from  $5 \text{ W m}^{-1} \text{ K}^{-1}$  to  $12 \text{ W m}^{-1} \text{ K}^{-1}$ , and we have used one of the lower estimates of the temperature sensitivity of P velocity, so we are estimating a minimal structure around the boundary.

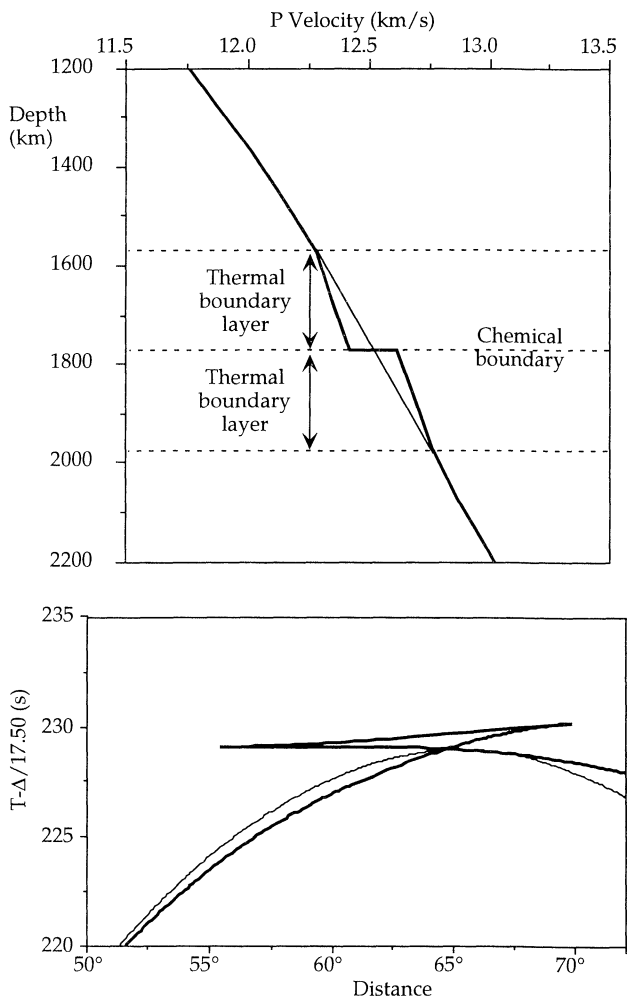
The chemical boundary is assumed sharp and placed at 1770-km depth. The vertical velocity and density gradients observed in the midmantle are nearly adiabatic [Birch, 1952]. However, a compositional boundary layer would imply significantly higher temperature and density below the boundary than above it. We must then assume that the nearly adiabatic gradients observed in Earth models like PREM [Dziewonski and Anderson, 1981] are caused by cancellation of thermal and compositional variations outside the thermal boundary layers. A greater intrinsic seismic velocity in the compositionally distinct material below the boundary must offset the velocity decrease from the rise in temperature across the thermal boundary layers. This cancellation is a bit surprising, since the greater density in the lower rock layer would normally be expected to reduce rather than raise seismic velocities.

Figure 1 shows our assumed compressional velocity as a function of depth. The thermal boundary layers above and below the chemical boundary are modeled as linear gradients 200 km wide. We do not perturb the shear velocity or density structure since they have little effect on grazing P waves. The thermal boundary layer just above the chemical boundary is slower than PREM, since it has a similar composition to the overlying rock, but higher temperatures. The thermal boundary layer just below the chemical boundary is faster than PREM, since it has similar composition to the underlying rock but lower temperatures.

### 3. Synthetic Seismograms

Figure 2 shows the seismograms that would result from the chemical boundary depicted in Figure 1. A

### P-velocity effect of mid-mantle chemical boundary



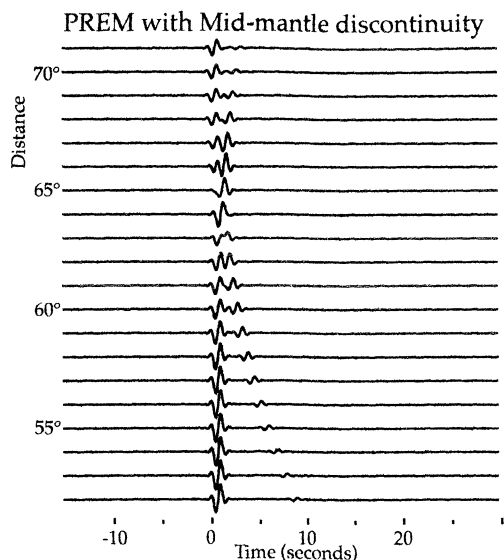
**Figure 1.** (Upper) P wave velocity structure for hypothesized midmantle chemical boundary (thick line) compared to PREM (thin line). The velocity perturbations are a combination of a contrast in composition and thermal boundary layers above and below the compositional boundary. The depth of a hypothesized compositional change and the depth extents of two thermal boundary layers are shown. (Lower) P wave travel time as a function of distance through this structure computed by ray tracing.

clear triplication is visible, although it is weaker than those present in the distance range  $15^\circ$  to  $30^\circ$  caused by transition zone phase changes near 410 and 660-km depths. Across more than  $10^\circ$  distance, from  $58^\circ$  to  $68^\circ$ , waveform complications are visible. Despite the small differences in the times of first P energy arrival, as shown in Figure 1, distinct later arrivals are produced.

The predicted signature of a flat chemical boundary would be most visible in high-frequency waves. The synthetics have the most power near 0.8-s period, and for longer period waves the separate arrivals would merge into more subtle waveform variations with distance.

### 4. Observations in California

The synthetic seismograms presented above show that the signature of a compositional boundary layer would be multiple arrivals separated by up to two



**Figure 2.** Synthetic seismograms for the hypothesized midmantle chemical boundary structure shown in Fig. 1. The reflectivity method is used [Fuchs and Muller, 1971]. Seismograms are aligned to the arrival time in the PREM model. Only P velocity is varied from the PREM model. We computed additional runs not shown to verify that S velocity and density structure have little influence on grazing P waveforms and amplitudes.



**Figure 3.** Map of earthquake network locations. The diamonds are events recorded by the Northern California Seismic Network (NCSN), marked by triangles, and the circles are events recorded by the Southern California Seismic Network (SCSN), marked by upside-down triangles.

seconds, sometimes with the later arrival larger than the initial arrival. The range and strength of the arrivals would depend on the local topography of the boundary, but plausible boundary structures would result in grazing rays for many source-receiver paths. We cannot test all boundary geometries in this paper, but rather concentrate on dense network data that would show such complications, if present.

We examine network data from California. Briefly, the bad and noisy traces were eliminated. The remaining traces were aligned to an early peak in the P wave. Nineteen events in the distance range 60° to 70° were examined, and 9 were rejected for having P-wave durations of more than 8 seconds. The remaining 10, listed in Table 1 and located in Figure 3, had estimated P wave durations ranging from 1 to 4 seconds. These data were collected and processed to examine earthquake source processes [Vidale and Houston, 1993]. Since the

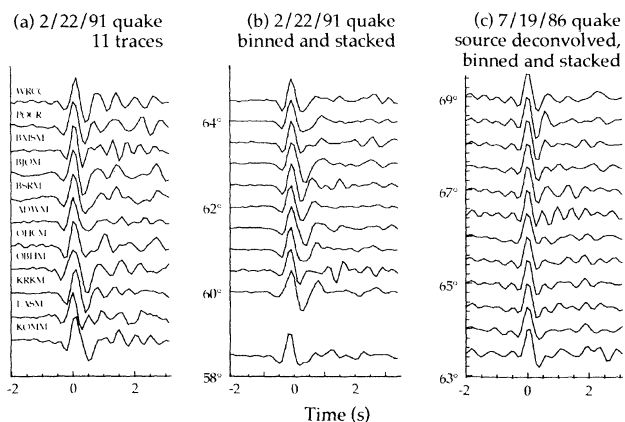
data were gathered for an independent study without consideration of waveform variation across the array, there is no bias in our sampling, although our coverage of the Earth is far from complete.

In the 5 smallest events, there is no evidence of variation in the waveform of the initial P arrivals. An example of these data is shown in Figures 4a and 4b. In both the binned data and the individual traces, little coherent waveform variation is seen. The biggest waveform variation may be the presence of a bigger negative swing near +0.5 s in the distance range 60° to 62° than at greater ranges.

**Table 1.** Earthquakes examined

Date	Array	Lat.	Lon.	Depth	Moment
09/15/82	SCSN	-15°	-71°	152 km	$3.3 \times 10^{25}$
02/01/84	SCSN	49°	147°	565 km	$3.6 \times 10^{25}$
04/20/84	SCSN	50°	149°	581 km	$2.9 \times 10^{25}$
05/01/85	NCSN	-9°	-71°	599 km	$8.3 \times 10^{25}$
07/19/86	SCSN	47°	151°	151 km	$0.3 \times 10^{25}$
08/12/87	NCSN	14°	-59°	54 km	$1.5 \times 10^{25}$
08/14/88	SCSN	55°	153°	645 km	$1.5 \times 10^{25}$
02/16/91	NCSN	48°	154°	44 km	$3.6 \times 10^{25}$
02/22/91	NCSN	-7°	-75°	142 km	M = 5.1
04/09/91	NCSN	-10°	-75°	135 km	$0.5 \times 10^{25}$

Parameters are from the Harvard CMT catalog, except for the event on 2/22/91, which is from a recent relocation [Engdahl et al., 1998]. Moment is in dyne-cm.



**Figure 4.** (a) 11 aligned traces from 2/22/91 event. (b and c) Seismograms sorted into 0.5° distance bins and stacked. (b) Stacks of aligned P waves from the 2/22/1991 earthquake, which had a short source duration. (c) Stacks of deconvolved P waves from the 7/19/86 earthquake. The deconvolution is calculated by spectral division with a "waterlevel" for stabilization [Clayton and Wiggins, 1976]. Between 2 and 15 seismograms contribute to each stack.

The 5 largest events, the four earliest events and the 2/16/91 event, had earthquake durations of 2 seconds or more. These larger events also had better signal-to-noise ratios than did the smaller ones. We removed the waveform complexities arising from a several-second source duration by deconvolution of a source time function derived from stacking [Vidale and Houston, 1993] to produce impulsive waveforms to search for triplicated arrivals. For the smaller events, there was already an impulsive source time function in the raw seismograms and too little bandwidth with sufficiently good signal-to-noise ratio, so that deconvolution did not improve the waveform resolution.

Figure 4c shows the binned seismic section for the 7/19/1986 event. The source time function for this event lasts 2 to 3 seconds, but is compressed to about a second-long pulse with minor ringing before and after the pulse by deconvolution. Again, little waveform variation is observed. The biggest difference is that an extra swing near +0.5 s appears near 68° to 69° distances, which isn't visible at closer ranges.

## 5. Conclusion

Given the great significance of determining whether the lower mantle is compositionally layered [Tackley, 2000], diagnostics for testing mantle models are sorely needed.

Our simple experiment shows that if a compositional boundary is present deep in the mantle, it should produce distinctive waveform variations in short-period P waves. Some have suggested that the intrinsic difference in seismic velocity from different compositions and the difference in temperature between material above and below the boundary could prevent seismic detection of the boundary. We show that the boundary would still be seismically visible because of the extra velocity structure that would be caused by thermal boundary layers.

We do not see the waveform variations that would be diagnostic of a chemical boundary in stations in California, nor have such variations in direct-P-wave arrivals been published, to our knowledge, for other areas. These geographically-limited observations tend to favor models in which the midmantle is well-mixed.

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