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# Preferential detection of the Lehmann discontinuity beneath continents

Yu J. Gu, Adam M. Dziewonski, and Göran Ekström

Department of Earth and Planetary Sciences, Harvard University, Cambridge, Massachusetts

**Abstract.** We perform a global survey for the presence of the Lehmann discontinuity using ~20,000 long-period $SS$ precursors. This data set is highly sensitive to upper mantle reflectors and the coverage is more complete than in previous studies. Our survey indicates that the Lehmann discontinuity is a local feature that is observed under continents more than twice as often as it is observed under oceans. We observe significant variations in travel times and waveforms associated with this shallow mantle reflector, indicating its complexity and lateral depth variations. Little signal is detected on the continent-scale stacks of the $SS$ precursors, which provides further evidence for the intermittent and variable nature of the Lehmann discontinuity.

## Introduction

There has been much discussion during the past two decade about the relation between surface tectonics, continent evolution, and mantle convection. Efforts from a variety of disciplines, including direct sampling and analysis of xenoliths, remote sensing using seismic waves, and numerical modeling, have contributed significantly to the understanding of the rheology, phase transitions, and convective flow in the upper mantle. One of the debates that emerged from these efforts is the existence of the Lehmann discontinuity.

The Lehmann discontinuity (also known as L discontinuity or 220-km discontinuity) was first observed from seismic refraction studies in Europe and North America [*Lehmann*, 1959, 1961]. *Jordan* [1975, 1978] introduced the tectosphere hypothesis which explained this discontinuity by a petrologically distinct chemical boundary layer under continental cratons. Recent studies of the underside reflection of depth phases [e.g., *Vidale and Benz*, 1992], ScS reverberations [*Revenaugh and Jordan*, 1991; *Gaherty and Jordan*, 1995], and $P$-to-$S$ converted waves [*Bostock*, 1996, 1999] provide further evidence for the regional presence of this discontinuity under continents and island arc regions. It has also been frequently associated with a rheological boundary separating a rigid continental plate from a more plastic, convecting mantle below.

There have been questions, however, regarding the existence of the Lehmann discontinuity (hereafter referred to as the L discontinuity). For example, studies of long-period $SS$ precursors [*Shearer*, 1991, 1993; *Gossler and Kind*, 1996; *Gu et al.*, 1998; *Flanagan and Shearer*, 1998] found little evidence for its presence from global- or continent-scale stacking of $SH$-component recordings. This result, as well as a significantly improved $SS$ precursor data set, motivate us to undertake a more detailed global survey of the L discontinuity. Our analysis using a cap-averaging scheme shows the intermittent presence of this discontinuity. By comparing this result with a continent-scale stacking of the $SS$ precursors, we can further constrain its location and depth variations.

## Data and approach

Our data set includes recordings collected by GDSN, IRIS, GEOSCOPE, and other seismic networks from earthquakes between 1989 and 1999. We use only shallow events (with Harvard CMT depth $\leq$ 75 km), thereby limiting the effects of depth phases (e.g., $sS$) and equalizing the source for more consistent stacking results. The epicentral distance between source and receiver is restricted to lie between 100° and 160°, where the amplitudes of the secondary reflections are the most pronounced. These criteria result in 21,000 $SH$-component seismograms (nearly 20,000 after interactive evaluation); this is substantially more than those used in earlier studies of $SS$ precursors. We use 412 partially overlapping caps with a radius of 10° to average over the observations. Figure 1a shows the number of seismograms used in the stacking procedure for each cap location. The best coverage is in the Pacific with as many as 800 seismograms in certain caps. Figure 1b shows the azimuthal coverage of the data set. Caps with star-like symbols (with short lines in several directions) have a better azimuthal coverage than those with long lines in one or two directions only. The central Pacific, Africa and South America have the best azimuthal coverage, while the coverage in China, Australia, and the polar regions is relatively poor.

The stacking approach is similar to that used in the study of the global topography of the 410- and 660-km discontinuities by *Gu et al.* [1998]. A synthetic seismogram is computed using PREM [*Dziewonski and Anderson*, 1981] for each path and receiver pair; the predicted $S220S$ phase in the stacked PREM synthetic seismograms provides a convenient reference for the detection of $S220S$ in the data stacks. We classify the detection of the L discontinuity in four empirical categories based on the robustness of the L reflections: (1) "uncertain" (due to insufficient data or complexities in the stacked waveforms), (2) "not detected" (when no detectable arrival is found that would support an L reflection), (3) "detected but weak" (a seismic arrival is observed which can be associated with the presence of the L discontinuity, but the

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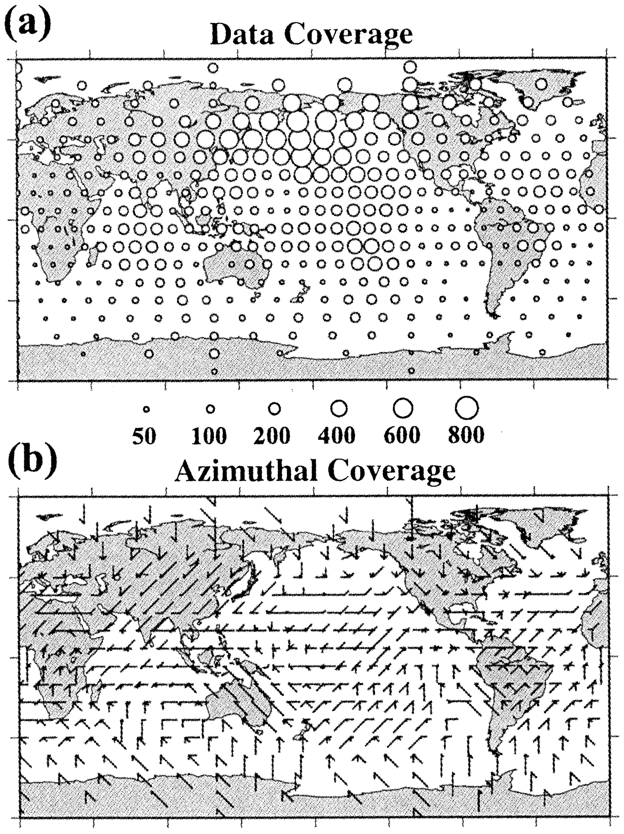

**Figure 1.** (a) The number of seismograms (used in the stacking procedure) at each cap location. (b) Azimuthal coverage at the cap locations. We divide the 360° angle uniformly into eight sectors. For a given cap, the length of the line in a sector is proportional to the percentage of measurements (over the total number of measurements within this cap) which have back-azimuths within that sector.

uncertainties in the measurements are large due to small reflection amplitudes or complexities in the waveforms), and (4) "clear detection" (the most robust observations of the L discontinuity).

Due to the potentially small velocity jump ($< 5\%$ in PREM) associated with this discontinuity, the uncertainties in the travel time measurements are considerably larger than those of the 410- and 660-km discontinuities. Thus we focus on the detection, rather than the depth variation, of this discontinuity. Furthermore, we recognize that since the long-period waves used in this study have a dominant period of 20 sec, the signals from the L discontinuity could result from a sharp change in velocity ($v_{SV}$-sensitive) or a velocity gradient spanning less than 50 km.

## Results

Figure 2a shows the stacks from three caps where the L discontinuity is well detected. Clear arrivals of $S410S$ and $SS$ are evident both in the synthetic (using PREM) and in the data stack. An additional arrival between these two phases, as marked by the arrows, exist in all three data stacks. Although this arrival appears to be associated with those predicted by PREM (shown by thin solid lines), the travel times and waveforms vary significantly from region to region. For example, the observed differential travel time of $S220S - S410S$ under Indonesia is several seconds smaller than that predicted by PREM. Considering that the average depth of the 410-reflector is 10 km deeper than 400 km (in PREM), this would indicate the presence of a considerably deeper reflector (~240 km). The data stack from the central Siberia, on the other hand, shows a much shallower L discontinuity. The slight shift in phase in the observed $S220S$ suggests complexities under this region. The L reflection under India appears to occur at a depth ~220 km, though its high amplitude would suggest a larger velocity jump than that of PREM. Figure 2b shows three examples where the L reflection is detected but exhibits a more complex nature. Except for the data stack in Kurile Islands, where the L reflection is relatively weak, the examples in Figure 2b show arrivals in the expected $S220S$ time window that differ significantly in amplitude and phase from the predicted arrivals. The origin of these rather anomalous phases cannot be explained by a simple horizontal boundary that marks an increase in seismic velocity. The difference in polarity with the predicted underside reflections may suggest the presence of complex velocity structure, possibly a velocity decrease at the discontinuity. The majority of the caps, however, do not show a notable discontinuity near 220 km. This is demonstrated in Figure 2c where no visible arrival is observed in the $S220S$ time window (shaded region).

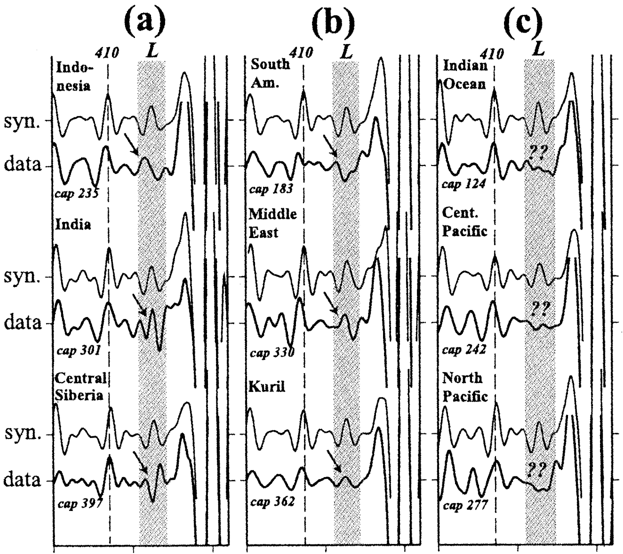

**Figure 2.** (a) Three stacks that show clear arrivals of $S220S$. The thick solid lines show the data seismograms, and the thin solid lines show the corresponding synthetic seismograms computed using PREM. (b) Three stacks where $S220S$ is marginally detected. Some of the L reflections in the data stacks appear to have different polarities from those of the synthetic, as shown by caps in the South Atlantic and Middle East. The cap under Kurile Islands shows a modest L reflection. (c) Three stacks that do not show detectable $S220S$ arrivals; their expected locations are indicated by question marks. The shaded region shows the travel time window where $S220S$ is expected.

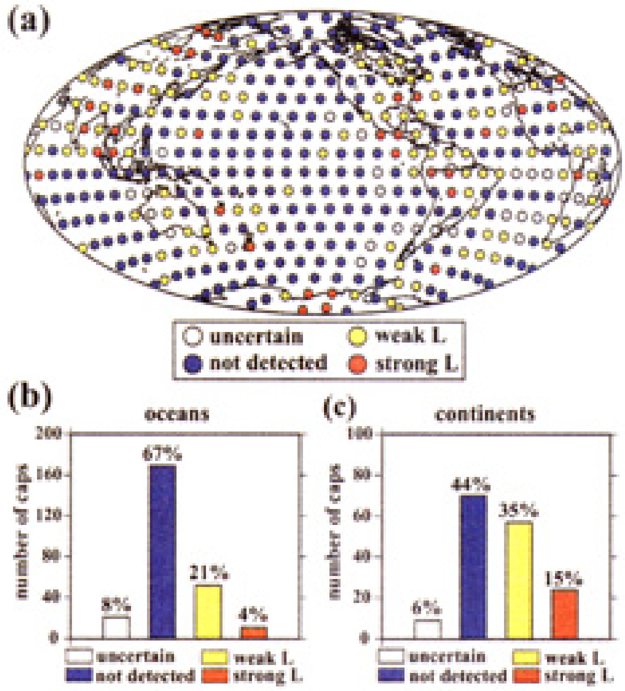

**Figure 3.** (a) A global survey of the L discontinuity. The detection levels are as indicated for the four categories (see text for details). A greater percentage of continental regions show evidence for the L discontinuity. Data under Eurasia and Africa show the most robust observations of this discontinuity. (b) Statistical analysis of the L discontinuity for oceanic regions. The percentage values are with respect to the total number of caps in each region. (c) Similar to (b), but for continental regions. The majority of the caps under the oceans (67%) do not show a discontinuity near 220 km, while half of the caps under the continents do.

The result of our global survey of the L discontinuity is presented in Figure 3a. To first order, this discontinuity appears to be an intermittent feature, as ~60% of the caps show little indication of its presence. The best detection of $S220S$ is concentrated in Eurasia, the Philippines, Africa and South America (shown in red). The estimated depths at these locations range from 200 km to 270 km, with an average value of 235 km and uncertainties ranging from 2 km to 20 km; such a range of depth perturbations is comparable to that observed by *Revenaugh and Jordan* [1991] in the western Pacific. The L discontinuity under the western part of North America generally shows low amplitudes or complex waveforms. Also evident is an east-west difference in the occurrence of the L discontinuity under Australia, as caps in the west generally show more pronounced L reflections than those in the east. Interestingly, this feature appears to be slightly correlated with the east-west difference in the shear velocities at depths of 200–300 km [*Simons et al.*, 1999; *Gu et al.*, 2001] which have been associated with the deep roots of continents. Robust L reflections are also observed in the island arcs of Loyalty Island and New Zealand at slightly shallower depths than 220 km. A visual examination shows that the majority of the caps in the vast oceanic regions, particularly the Pacific and Indian oceans, do not have detectable $S220S$ arrivals; however, a number of caps in the Atlantic do suggest the local presence of this discontinuity.

A statistical analysis of our observations is shown in Figures 3b and 3c. Over 65% of the caps under the oceans (Figure 3b) do not show a visible discontinuity near 220 km depth. Because oceanic regions occupy nearly two-thirds of Earth's surface, the scarcity of the L discontinuity under these regions largely explains the "missing" $S220S$ arrival in the global stacks of *Shearer* [1991]. On the other hand, a much greater percentage of caps under the continents (50% in comparison with 25% under the oceans; Figure 3c) show either a small/complex or a pronounced L reflection. The striking difference between the most robust observations under the continents (15%) and oceans (4%) clearly suggests that the L discontinuity is an intermittent discontinuity that is significantly more visible under the continents.

## Discussion

*Shearer* [1991] analyzed long-period $SH$-component seismograms and observed no distinct mantle discontinuity above 400 km; this was evidenced by stacks of both the global data set and subsets restricted to continental platforms and shields. These findings were supported by *Gu et al.* [1998] using a similar approach and a significantly bigger data set. The results from our global survey of the L discontinuity are consistent with those two studies in that the L discontinuity is only a local feature; it is detected only in 25% of the caps under oceans and half of the caps under continents. The lack of an L reflection in the platform and shield stacks of *Shearer* [1991] does not necessarily represent a contra-

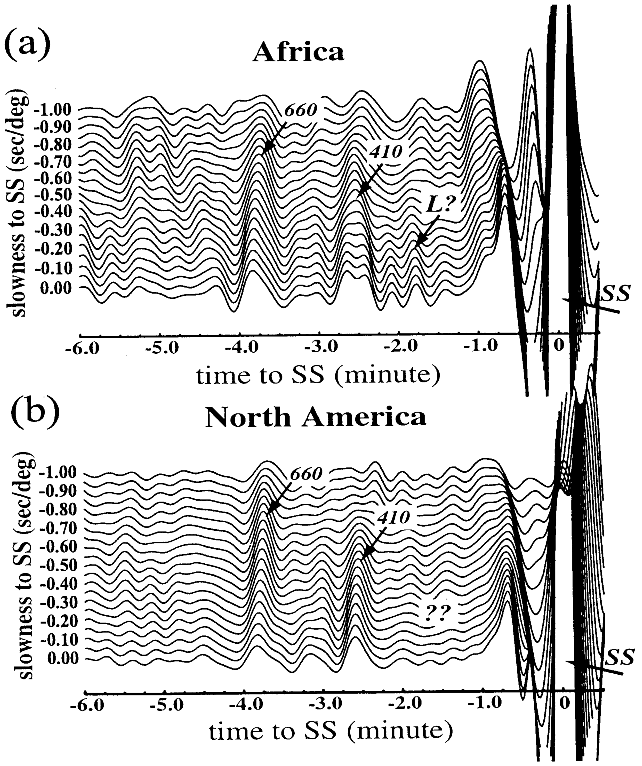

**Figure 4.** Slant-stack comparison of the regional occurrence of the L discontinuity under (a) Africa, and (b) North America. Clear arrivals of $S410S$, $S660S$, and a weak L reflection are observed under Africa, but there is little evidence for an L reflection under North America.

diction. Instead, it presents a constraint on the intermittent nature and strong depth variation of this reflector. Because of the potentially complex nature of the L discontinuity and its relatively modest seismic velocity jump (in comparison with that of the 410- and 660-km discontinuities), great variability is expected both in the waveforms and in the travel times of the L reflection (see Figures 2 and 3). These variations generally lead to destructive interference and the signal of $S220S$ can be effectively averaged out by phase equalization of the data covering major continents, or a combination of continents. This "muting" effect is illustrated in Figure 4 where we examine the regional averages of data for Africa and North America. We use a stacking approach that is based on a simple relationship between the relative slowness ($s$) with respect to $SS$, epicentral distance $\Delta$, and a time shift ($\delta t$) to each trace (see *Gossler and Kind* [1996]):

$$\delta t(\Delta) = s(\Delta - \Delta_r), \tag{1}$$

where $\Delta_r$ is the reference distance of 130°. After all of the individual traces are aligned on $SS$ (step 0), the time delays are computed at 20 steps (and stacked) with a steady decrement of 0.05 sec/° in slowness from the predicted slowness of $SS$. Figure 4a shows the result of this procedure for all of the reflection points under Africa. In addition to clear peaks associated with the 410- and 660-km discontinuities, a modest peak is observed at $\sim$105 sec from the peak location of $SS$. The amplitude is significantly smaller than that of the predicted $S220S$ phase and the travel time is $\sim$15 sec earlier than the predicted arrival time of $S220S$. If this peak indeed results from an underside reflection off a shallow mantle reflector, it would suggest a weaker (and perhaps more complex) reflector with a regionally averaged depth of $\sim$250 km. More lateral variations are observed under North America (Figure 4b), where there is little indication of L discontinuity in the regional stack. The low visibility of $S220S$ in these stacks is consistent with results obtained from the global stacks of *Shearer* [1991] and regional stacks of *Gu et al.* [1998], but is significantly different from those obtained in the cap-scale stacking of this study.

Our results provide new evidence for the local existence of the Lehmann discontinuity. This discontinuity is mostly observed under continents, which suggests possible differences in rheology or composition between oceans and continents at depths below 200 km. The presence of this discontinuity and its variability in depth may also be explained by a transition from an anisotropic lithosphere to a more isotropic material in the lower part of the continental lithosphere [e.g., *Gaherty and Jordan*, 1995]. Our results are consistent with earlier studies using secondary reflections and conversions [e.g., *Gaherty and Jordan*, 1995; *Vidale and Benz*, 1992; *Bostock*, 1996], and the presence of an L discontinuity under Russia is in good agreement with the findings of *Mechie et al.* [1993] and *Ryberg et al.* [1995] from seismic refraction data. Results from a recent study by *Deuss and Woodhouse* [2000] using an independent $SS$ precursor data set also support the main observations of this study.

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A. M. Dziewonski, G. Ekström, and Y. J. Gu, Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138. (dziewons@eps.harvard.edu; ekstrom@eps.harvard.edu; gu@eps.harvard.edu)

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