Seismic evidence for accumulated oceanic crust above the 660-km discontinuity beneath southern Africa

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[1] High-pressure assemblages of subducted oceanic crust are denser than the normal upper mantle but less dense than the uppermost lower mantle. Thus subducted oceanic crust may accumulate at the base of the upper mantle. Direct observational evidence for this hypothesis, however, remains elusive. We present an analysis of a negative-polarity shear wave converted from compressional wave at a seismic discontinuity near 570–600 km depth beneath southern Africa. The negative polarity of the converted phase indicates a $\sim$2.2 $\pm$ 0.2% S-velocity decrease with depth at the seismic discontinuity. This velocity reduction is associated, however, with a low velocity contrast at the 660-km discontinuity. The exsolution of Ca-perovskite in former oceanic crust at depth greater than 600 km and the associated small volume fraction of ringwoodite are plausible explanations for the apparent paradox between the negative velocity discontinuity and the low velocity contrast at the 660-km discontinuity. *INDEX TERMS:* 1030 Geochemistry: Geochemical cycles (0330); 7218 Seismology: Lithosphere and upper mantle; 8124 Tectonophysics: Earth's interior—composition and state (1212); 9305 Information Related to Geographic Region: Africa. **Citation:** Shen, Y., and J. Blum, Seismic evidence for accumulated oceanic crust above the 660-km discontinuity beneath southern Africa, *Geophys. Res. Lett.*, *30*(18), 1925, doi:10.1029/2003GL017991, 2003.

1. Introduction

[2] Subducted oceanic crust contributes significantly to the chemical evolution of the Earth's mantle. Many ocean-island basalt (OIB) and mid-ocean ridge basalt (MORB) samples have chemical characteristics indicative of recycled oceanic crust in their sources [e.g., *Hofmann and White*, 1982; *Rehkaemper and Hofmann*, 1997]. What remain controversial are the distribution of subducted oceanic crust in the mantle and the mechanism of its entrainment into the MORB and OIB sources.

[3] Subducted oceanic crust undergoes phase transformations under high pressure and temperature. It re-crystallizes to an eclogitic assemblage and then transforms into a majorite-bearing assemblage (garnetite) at the depth of 300–450 km [*Irifune and Ringwood*, 1993]. The former oceanic crust is denser than the upper mantle, but less dense than the uppermost lower mantle [*Ringwood*, 1991]. Near 720 km depth, majorite transforms into a perovskitite lithology, which is again denser than the lower mantle [*Hirose et al.*, 1999].

[4] As a consequence of neutral buoyancy, subducted oceanic crust may accumulate above the 660-km discontinuity [*Ringwood*, 1967; *Anderson*, 1979; *Ringwood*, 1991]. Numerical simulations and theoretical analyses have shown conditions under which a subducted slab stagnates at the 660-km discontinuity [*Kerr and Lister*, 1987] and oceanic crust decouples from the slab [*van Keken et al.*, 1996; *Karato*, 1997]. More favorable conditions for gravitational trapping of oceanic crust above the 660-km discontinuity probably existed during the Archaean [*Ringwood*, 1991], when the mantle was hotter than present [*Bickle*, 1986]. Theoretical calculations have also illustrated that mantle plumes may entrain former oceanic crust that has accumulated above the 660-km discontinuity [*Yasuda and Fujii*, 1998].

[5] Despite the logic of mineralogical and geodynamic arguments for the possible accumulation of subducted oceanic crust above the 660-km discontinuity, direct observational evidence remains elusive. Yet, the difference in mineralogical assemblages between subducted oceanic crust and the pyrolitic [*Irifune*, 1987] or piclogitic [*Duffy and Anderson*, 1989] mantle may lead to seismic signatures discernable by increasingly sensitive seismic arrays and data analysis. In this paper we document shear (S) waves converted from copressional (P) waves at a negative velocity discontinuity (a velocity reduction) near 590 km depth beneath southern Africa. The negative discontinuity and the associated anomalously low velocity contrast at the 660-km discontinuity can be attributed to a layer of accumulated oceanic crust at the base of the upper mantle beneath the study area.

2. Negative Velocity Discontinuity in the Transition Zone Beneath Southern Africa

[6] The Archaean cratons in southern Africa are believed to have developed as a rapid series of magmatic and tectonic processes in the presence of subduction zones [e.g., *Abbott*, 1991]. Recent seismic experiments in southern Africa had over 100 broadband stations (Figure 1) [*James et al.*, 2001], providing an opportunity to determine whether subducted oceanic crust is present at the base of the upper mantle in an area of ancient subduction. From body waves recorded by the broadband seismic stations in southern Africa, we selected over 3300 radial receiver functions with noise levels less than 0.1 times the amplitude of the direct P-wave on the vertical

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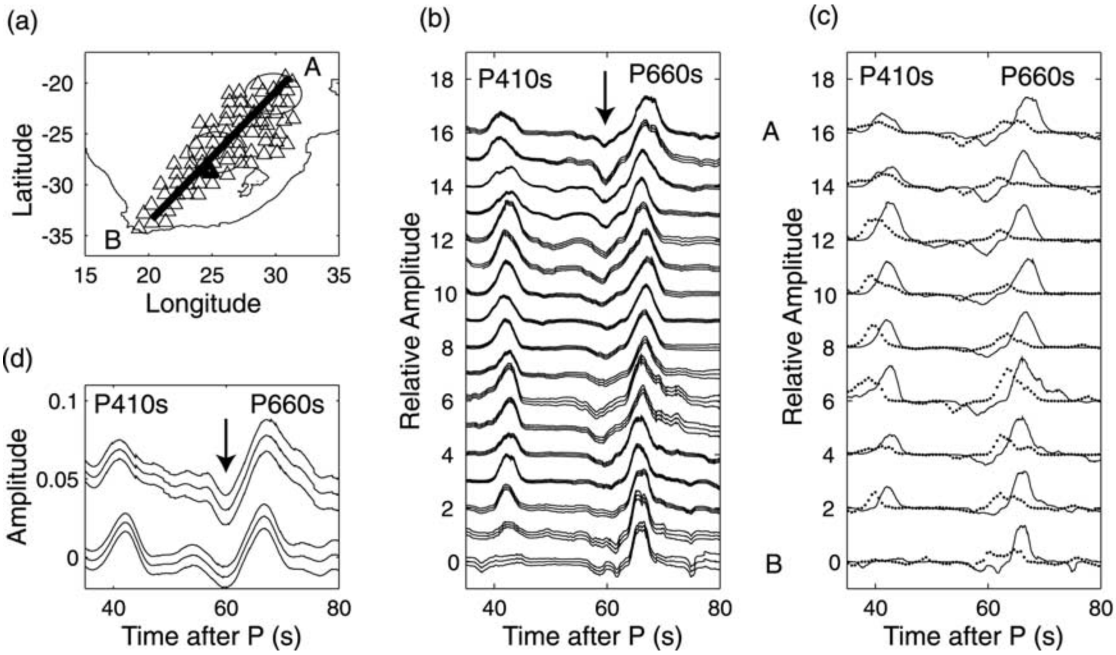

Figure 1. (a) Locations of broadband seismic stations (triangles) and the profile of the receiver function stacks (line). Circles with a radius of 2° outline two of the overlapping patches used in stacking. (b) Waveforms of the stacked receiver functions along the profile in (a) and their 95% confidence limits determined by bootstrap [*Efron and Gong*, 1983]. Arrow marks the arrival of the negative-polarity phase. An *n*th root ($n = 2$) stacking process [*Kanasewich et al.*, 1973] is used to enhance coherent phases and suppress random noise. (c) A comparison of the receiver functions stacked along Pds moveout curves (solid lines) and reverberation moveout curves (dotted lines). Every other trace in (b) is shown for legibility. (d) Waveforms of two linearly stacked receiver functions from the two patches outlined in (a) and their 95% confidence limits. The bottom trace corresponds to the patch near the center of the array. The scale of the vertical axis is relative to the amplitude of P wave on the vertical component. The top trace has been shifted upwards by 0.05.

component. In order to detect weak P-to-S conversions from seismic discontinuities beneath the stations, we divided the study area into circular overlapping patches with a radius of 2°. Receiver functions having converted waves piercing the same patch at a given depth in the mantle were gathered and stacked [*Dueker and Sheehan*, 1997; *Shen et al.*, 1998a]. Relative traveltime delays across the seismic networks were used as a first-order approximation to correct receiver functions for velocity heterogeneity beneath the stations.

[7] The stacked receiver functions (Figure 1b) reveal a consistent negative-polarity phase between the P-to-S conversions from the 410- and 660-km discontinuities (P410s and P660s, respectively). The fact that no consistent negative-polarity phase appears after P660s indicates that the identified phase, which is 6–9 s before P660s, is not a side-lobe of the finite-frequency P660s arrival. This negative-polarity phase was noted but unexplored in a previous study of the area [*Gao et al.*, 2002]. A similar negative-polarity phase was observed beneath the East Pacific Rise [*Shen et al.*, 1998b], but limited ocean-bottom seismic data prevented further analysis.

[8] Stacking along moveout curves for reverberations from hypothetical shallow discontinuities [*Gurrola et al.*, 1994] reduces the amplitude of this negative-polarity phase as well as those of P410s and P660s (Figure 1c), confirming that the identified phase is not a reverberation. The average amplitude of the negative-polarity phase in linear stacks (Figure 1d) is $-1.7 \pm 0.1\%$ of the amplitude of P wave on the vertical component, or 0.73 ± 0.05 and 0.59 ± 0.04 times the amplitudes of P410s and P660s, respectively. The amplitudes have been corrected for differences in P wave incidence angles to a ray parameter of 0.0573 s/km (equivalent to the ray parameter of the direct P wave from a shallow earthquake at an epicentral distance of 67°). The negative-polarity phase suggests a $2.2 \pm 0.2\%$ velocity decrease with depth at a discontinuity on average 72 ± 14 km above the 660-km discontinuity.

[9] Receiver functions shown in Figure 1 have a dominant period of ~15 s. Those having a dominant period of ~3 s show clear P410s and P660s but no significant negative-polarity phases preceding P660s, indicating that the velocity transition responsible for the negative-polarity phase must occur within a depth interval of 10–45 km, less sharp than the 410- and 660-km discontinuities.

3. Causes of the Negative Seismic Discontinuity in the Mantle Transition Zone

[10] No mineral phase transformation in a homogeneous pyrolitic or piclogitic mantle source has been found to significantly reduce seismic velocity at the base of the upper mantle. Excess temperature or compositional stratification near the base of the upper mantle could result in a reduction in seismic velocity and a negative seismic discontinuity. A thermal boundary layer with excess temperature, however, contradicts with the normal to thicker-than-normal transition zone observed beneath the study area [*Gao et al.*, 2002; *Blum and Shen*, 2002]. The 660-km discontinuity is generally associated with the phase transformation between ringwoodite and (Mg,Fe)SiO_3-perovskite plus (Mg,Fe)O-

magnesiowüstite. Because of the negative Clayperon slope of the phase boundary, excess temperature at the base of the upper mantle reduces the depth to the 660-km discontinuity and thus the transition zone thickness. A 72-km thick layer having a ~2% low velocity would increase the apparent transition zone thickness by 1.5 km, an order of magnitude less than the transition-zone thickness anomaly observed beneath southern Africa [*Blum and Shen*, 2002].

[11] While excess water content in an otherwise compositionally homogeneous mantle could reduce seismic velocity at the base of the upper mantle [*Inoue et al.*, 1998], it is difficult to envisage how a water-rich layer at the base of the upper mantle could remain subhorizontal like the negative-polarity phase observed beneath the study area (Figure 1) and be dynamically stable over time scales of 1–3 Gyr. Furthermore, a uniform reduction in S velocity beneath the negative discontinuity by ~2% (Figure 2) would result in a significant increase in the velocity contrast at the 660-km discontinuity and consequently an increase in the P660s amplitude. These are not observed. In contrary, the average amplitude of P660s observed beneath the study area (2.9 ± 0.1% of the amplitude of the P wave on the vertical component) is much smaller than the values predicted for iasp91 and in a global compilation (~6 ± 1%) [*Shearer*, 1991]. The S velocity contrast at the 660-km discontinuity beneath the study area is therefore unlikely greater than normal. Excluding areas having a thicker-than-normal (thickness >250 km and anomalously cold) transition zone yields essentially the same estimate of the P660s amplitude (3.0 ± 0.2%). We conclude that excess water content and other compositional variations that cause a reduction in seismic velocity throughout the ~72-km-thick layer at the base of the upper mantle (Figure 2) do not fit the low velocity contrast at the 660-km discontinuity.

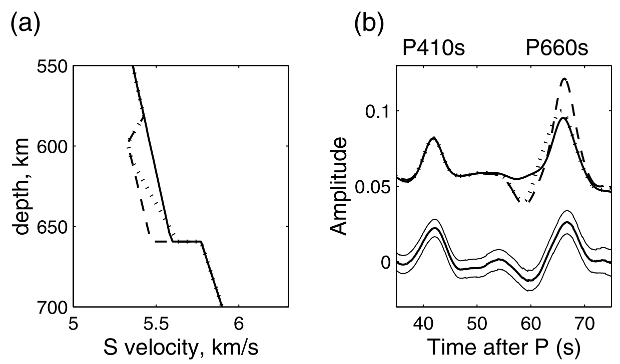

Figure 2. (a) Two possible scenarios may cause a negative-polarity P-to-S conversion near 590 km depth: a uniform reduction in velocity at the base of the upper mantle (dashed line) and a velocity reduction near 590 km followed by a greater than normal velocity gradient (dotted line). The reference shear velocity structure (solid line) is a modified iasp91 model [*Kennett and Engdahl*, 1991] with a smaller velocity contrast at the 660-km discontinuity to provide a better fit to the observed P660s amplitude. (b) The top traces are the synthetic receiver functions for the three velocity models in (a). Line styles match those in (a). Arrow marks the converted phase from the velocity reduction near 590 km depth. The waveform of a linearly stacked receiver function from the center patch in Figure 1a and its 95% confidence limit are shown for comparison. The top traces are shifted upwards by 0.05.

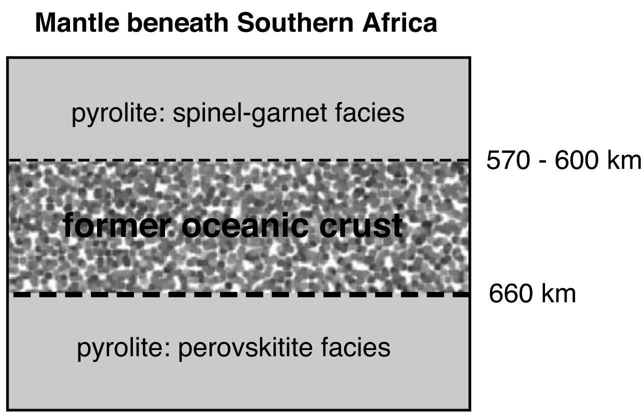

Figure 3. Schematic diagram illustrates a possible petrological structure of the mantle transition zone beneath southern Africa. Subducted oceanic crust accumulates at the base of the upper mantle, forming a ~70 km thick layer with an upper limit near 570–600 km depth.

[12] Accumulated oceanic crust at the base of the upper mantle (Figure 3) or a mixture of the normal mantle and former oceanic crust provides a plausible explanation for the apparent paradox between the significant negative velocity discontinuity near 590 km depth and the low velocity contrast at the 660-km discontinuity. Majorite (majorite-garnet), the most voluminous mineral in subducted oceanic crust in the transition zone, has a lower seismic velocity than the average mantle [*Ita and Stixrude*, 1992]. The low velocity of majorite is partially balanced by the high velocity of stishovite [*Li et al.*, 1996], which is about 10% in volume in subducted oceanic crust in the transition zone [*Irifune and Ringwood*, 1987]. A recent review of measurements of the elastic constants supplemented by estimates based on systematics and first principles theoretical predictions suggests that subducted oceanic crust has a shear wave velocity that is ~2% lower than that of pyrolite at 530–630 km depth (*L. Stixrude*, per. comm.). At depth greater than 600 km, majorite begins to gradually exsolve $CaSiO_3$-rich perovskite [*Irifune and Ringwood*, 1987], which reaches 15–20% in volume at the base of the upper mantle and has a shear velocity 10% higher than the normal mantle (*Duffy and Anderson* [1989] and *L. Stixrude*, per. comm.). The Ca-perovskite exsolution could increase the shear wave of former oceanic crust by 1–2 percent from 600 km depth to the base of the upper mantle. This scenario is in general agreement with an anomalously large P-wave velocity gradient over a depth range of ~80 km around 660 km depth inferred from the travel times and waveforms of direct P waves beneath southern Africa [*Zhao et al.*, 1999]. Furthermore, a mantle assemblage rich in majorite-garnet (such as a mixture of the normal mantle and former oceanic crust) has a relatively small volume fraction of γ-spinel and consequently a small velocity contrast at the 660-km discontinuity.

[13] We note that a layer of accumulated oceanic crust tends to gravitationally maintain a subhorizontal upper limit, consistent with the geometry of the negative velocity discontinuity. Finally, eclogitic xenoliths from southern Africa, which have a starting composition of MORB and a depth

of origin in the transition zone [*Sautter et al.*, 1991], provide additional supporting evidence for subducted oceanic crust in the transition zone beneath southern Africa.

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