Earth and Planetary Science Letters 414 (2015) 45–57

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Frontiers paper

The seismic mid-lithosphere discontinuity

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ARTICLE INFO

Article history:
Received 6 September 2014
Received in revised form 12 December 2014
Accepted 14 December 2014
Available online 23 January 2015
Editor: M.M. Hirschmann

Keywords:
mid-lithosphere discontinuity
S receiver function
lithosphere–asthenosphere boundary
amphibole
anisotropy

ABSTRACT

Seismic S-wave receiver functions (SRF) are a uniquely powerful tool for imaging velocity discontinuities within the upper mantle. SRF data frequently contain negative phases at depths between ~80 and 100 km within the continental lithosphere, indicative of large and sharp velocity drops at these depths. In young, actively tectonic areas with thin lithosphere, this feature is generally interpreted as the lithosphere–asthenosphere boundary. However, in tectonically stable areas it occurs within the continental lithospheric mantle and has been termed the mid-lithosphere discontinuity (MLD). A significant velocity drop at such depths is unexpected and its cause is unknown. In this manuscript, we summarise the current observations and assess the main mechanisms that could produce such a feature. We find that changes in mantle iron content (Mg#) and elastically-accommodated grain-boundary sliding are unlikely to result in sufficiently large velocity decreases to produce an observable SRF response, while partial melt will generally only exist at greater depths within stable lithosphere. Radial and azimuthal seismic anisotropy are both capable of producing negative SRF phases. However, azimuthal anisotropy will not produce consistently negative phases independent of back-azimuth. Some geometries of radial anisotropy can produce consistent negative phases but such geometries are not observed universally and are hard to explain tectonically. Low-velocity minerals can cause sharp and large decreases in seismic velocity. Amphibole-rich layers are likely to form at MLD depths in metasomatised regions, making amphibole a possible cause for the MLD. However, some xenolith sections contain no amphibole, suggesting this may not be a universal explanation. A careful assessment of SRFs shows that the continental lithospheric mantle generally contains numerous positive and negative velocity discontinuities and is spatially heterogeneous. Long-period band-pass filtering can combine smaller features and may lead to the appearance of a larger and more coherent velocity decrease at the MLD than actually exists. We propose that many of the assessed mechanisms may be acting at different depths in different locations to produce numerous velocity discontinuities. The large MLD phase is likely to be commonly associated with amphibole but on current evidence there is no universal cause for the MLD.

1. Introduction

Where seismic shear-wave receiver function (SRF) studies (Farra and Vinnik, 2000; Zhou et al., 2000) have been carried out in the continents, they have consistently observed a decrease in seismic velocity at depths between ~60 and ~160 km and generally between ~80 and 100 km (Fig. 1) (e.g. Abt et al., 2010; Chen, 2009; Ford et al., 2010; Foster et al., 2014; Heit et al., 2007; Kumar et al., 2013; Savage and Silver, 2008; Sodoudi et al., 2013; Wittlinger and Farra, 2007; Wölbern et al., 2012). In some areas this seismic velocity decrease appears to be continuous between tectonically active areas and tectonically stable areas, such as across western USA (Foster et al., 2014) and across Australia (Ford et al., 2010). In tectonically active areas with thin lithosphere (~100 km thick), the velocity drop is generally interpreted as the lithosphere–asthenosphere boundary (LAB) (e.g. Ford et al., 2010; Foster et al., 2014; Heit et al., 2007). However, in stable continental and cratonic areas the lithosphere is ~150 to 300 km thick (Artemieva and Mooney, 2001; Carlson et al., 2005; Griffin et al., 2009; Jordan, 1978, 1988; Li et al., 2008; Schaeffer and Lebedev, 2013) and the cause for the velocity drop at ~80–100 km is not so clear. Indeed, it has been interpreted as a possible lithosphere–asthenosphere boundary (LAB) even in cratons (Rychert and Shearer, 2009), which is at odds with xenolith thermobarometry, heat flow and other geophysical data. It is therefore now widely agreed that this velocity reduction occurs at mid-lithospheric depths and it has been termed the mid-lithospheric discontinuity (MLD) (Abt et al., 2010).

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http://dx.doi.org/10.1016/j.epsl.2014.12.029
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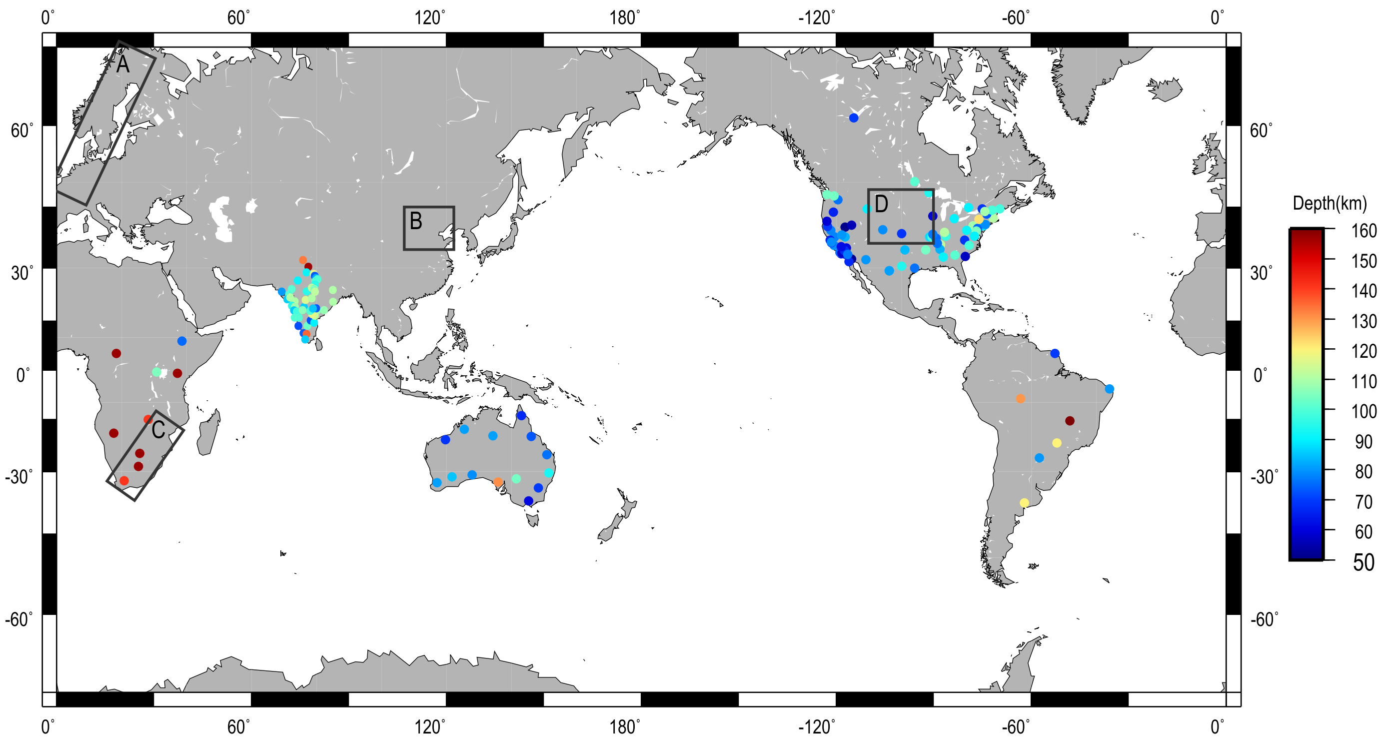

Fig. 1. Map of global observations of SRF data showing the depth to the largest negative phase beneath the Moho. Data are from North America (Abt et al., 2010; Rychert et al., 2007), Australia (Ford et al., 2010), South America (Heit et al., 2007), Africa (Hansen et al., 2009; Wölbern et al., 2012) and India (Kumar et al., 2013). Full coordinates are in the Supplementary Information. The mapped phases include those interpreted as the LAB (generally in actively deforming continental settings) or the MLD (generally in tectonically stable continental settings). Boxes A, B, C and D show the locations of dense station networks in Scandinavia (Kind et al., 2013), China (Chen, 2009, 2010), South Africa (Sodoudi et al., 2013) and western USA (Foster et al., 2014) for which SRF data have been published only as profiles. Although these cannot be displayed on this map, they show similar features to the single-station data, with large negative phases generally in the range of ~80 to 100 km.

The presence of a sharp drop in velocity at mid-lithospheric depths in stable continents is unexpected and intriguing. Mantle xenoliths suggest that the compositions and geotherms of stable continents generally vary smoothly at mid-lithospheric depths (e.g. Carlson et al., 2005; Griffin et al., 2009) and provide no obvious cause for such a significant velocity drop. The apparent universality of the MLD in continental lithosphere (within the limits of current observations) makes a universal explanation for its cause desirable but mantle xenoliths and geophysical data show that the varied tectonic histories of cratons have resulted in heterogeneous lithospheric mantle (Rudnick et al., 1998; Selway, 2014; Silver, 1996). Moreover, the apparent contiguity of the velocity drop between tectonically active and stable regions raises the question of whether a single mechanism also applies to active areas although they have very different geotherms, compositions and tectonic histories than cratons. Therefore, while the cause for the MLD is not immediately clear from our current understanding of continental evolution, this very fact makes it an exciting new observation that has the potential to significantly develop our understanding. In this contribution, we will summarise and describe the SRF observations and assess their possible causative mechanisms in terms of seismic implications and geological feasibility.

2. Summary of seismic observations

Seismic body waves are either compressional 'P' waves, where particle motion occurs in the direction of energy propagation or shear 'S' waves where particle motion occurs perpendicular to the direction of propagation. When a P or S_V (vertically polarised S) wave encounters a sharp, isotropic velocity contrast, some of the transmitted energy is converted into the opposite wave type, i.e. P to S_V (Ps wave) and S_V to P (Sp wave) (Fig. 2). P waves travel faster than S waves so distinct primary (S or P) and converted (Sp or Ps) waves will be recorded at the Earth's surface. In the receiver function (RF) method, the depth to the velocity contrast is determined by measuring the difference in arrival times and estimating the subsurface velocity structure (Julià, 2007; Kind et al., 2012; Langston, 1979; Rychert et al., 2007; Yuan et al., 2006). Primary P waves with converted Ps waves are P-receiver functions (PRFs) while primary S waves with converted Sp waves are S-receiver functions (SRFs). RF data have significantly better depth resolution of velocity contrasts (±10 to 15 km) than surface wave tomography (±~30 to 50 km) and body wave tomography (>50 km).

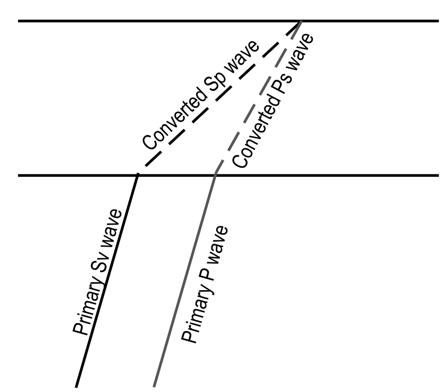

Fig. 2. When incident on a velocity discontinuity, some P wave energy will be converted to S wave energy (Ps wave) while some S-wave energy will be converted to P-wave (Sp wave) energy. Analysis of these converted waves at a seismic station (receiver) is referred to as the P-wave receiver function method (PRF) and the S-wave receiver function method (SRF) respectively.

PRFs are of limited use for determining lithospheric mantle structure since crustal P-wave reverberations (multiples) arrive at similar times to the slower Ps waves from mantle velocity con-