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Layering of subcontinental lithospheric mantle

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ABSTRACT

Recent seismic studies reveal a sharp velocity drop mostly at ~70–100 km depth within the thick mantle keel beneath cratons, termed the mid-lithosphere discontinuity (MLD). The common presence of the MLD in cratonic regions indicates structural and property layering of the subcontinental lithospheric mantle (SCLM). The nature and origin of the MLD, and many issues associated with the layering of the SCLM are essential to understand the formation and evolution of continents, and have become frontier subjects in the Earth sciences.

1. Introduction

Layering is one of the basic characteristics of the Earth. It has long been recognized that continental crust is structurally, compositionally and rheologically layered (e.g., [1,2]), and the upper and lower crust have different properties and behaviors both in short time periods (e.g., earthquake cycles, [1]) and during long-term geological evolution (>1 Ma, e.g., [3,4]). However, the structural variations with depth in the subcontinental lithospheric mantle (SCLM) remain elusive.

Recently, growing seismic evidence is emerging for the presence of a sharp discontinuity with a velocity decrease at ~60–160 km depth beneath continents (Fig. 1a) (e.g., [7,10–14]). The identification of this shallow mantle discontinuity has been made possible by the rapid development of dense seismic networks and increasing availability of numerous high-quality broadband seismic data. In young tectonic regions where the lithosphere is generally thin (~100 km), this discontinuity is considered to be the lithosphere-asthenosphere boundary (LAB) (e.g., [8,10,11]). However, beneath stable cratons where the lithosphere usually extends to >200 km depth (e.g., [15,16]), the discontinuity is interpreted as a mid-lithosphere discontinuity (MLD). The MLD thus marks the top boundary of a relatively low-velocity layer within the cold, high velocity cratonic mantle keel (e.g., [17,18]). Its common appearance is therefore a manifestation of vertical structural variation or layering within the cratonic SCLM (Fig. 2).

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2. Structural features of the MLD

Detailed structural information of the MLD is essential to elucidate the layering of the SCLM. Such information mostly comes from seismic studies using either body waves converted at the MLD (P- or S-receiver functions, e.g., [[22,23] and reference therein]) or reflected off the MLD (underside reflections directly from earthquake data, e.g., [24], or upperside reflections extracted by seismic interferometry, e.g., [25]) or surface waves that sample the shallow upper mantle depths (e.g., [17]), or both (e.g., [10]). These seismic studies suggest that the majority of observed MLDs cluster at ~70–100 km depth, although in some areas it appears shallower or deeper (Fig. 1c). Besides the relatively narrow depth range of occurrence, the MLD is also featured as a strong seismic velocity discontinuity. The shear-wave velocity (*Vs*) drop at the MLD is constrained to range from ~2% to over 10%, and generally occurs over a depth range of no more than 30–40 km (e.g., [12,23]). Interestingly, both the depths and sharpness (thickness and magnitude of velocity drop) of the MLD beneath cratons are broadly comparable to those of the LAB in tectonic regions (e.g., [5,7,10,26]) (Fig. 1b and c and Fig. 2). In some cases, the cratonic MLD and the LAB in neighboring young tectonic areas are imaged as one apparently continuous discontinuity (e.g., [27]). The strong MLD also appears structurally similar to the LAB of oceanic lithosphere (e.g., [28,29]), but differs considerably from the deeper cratonic LAB that is usually a weak discontinuity or a gradual velocity transition and thus difficult to detect (e.g., [11,12,15]).

In addition to the reduction in seismic velocity, vertical variations in physical and chemical properties were also reported at

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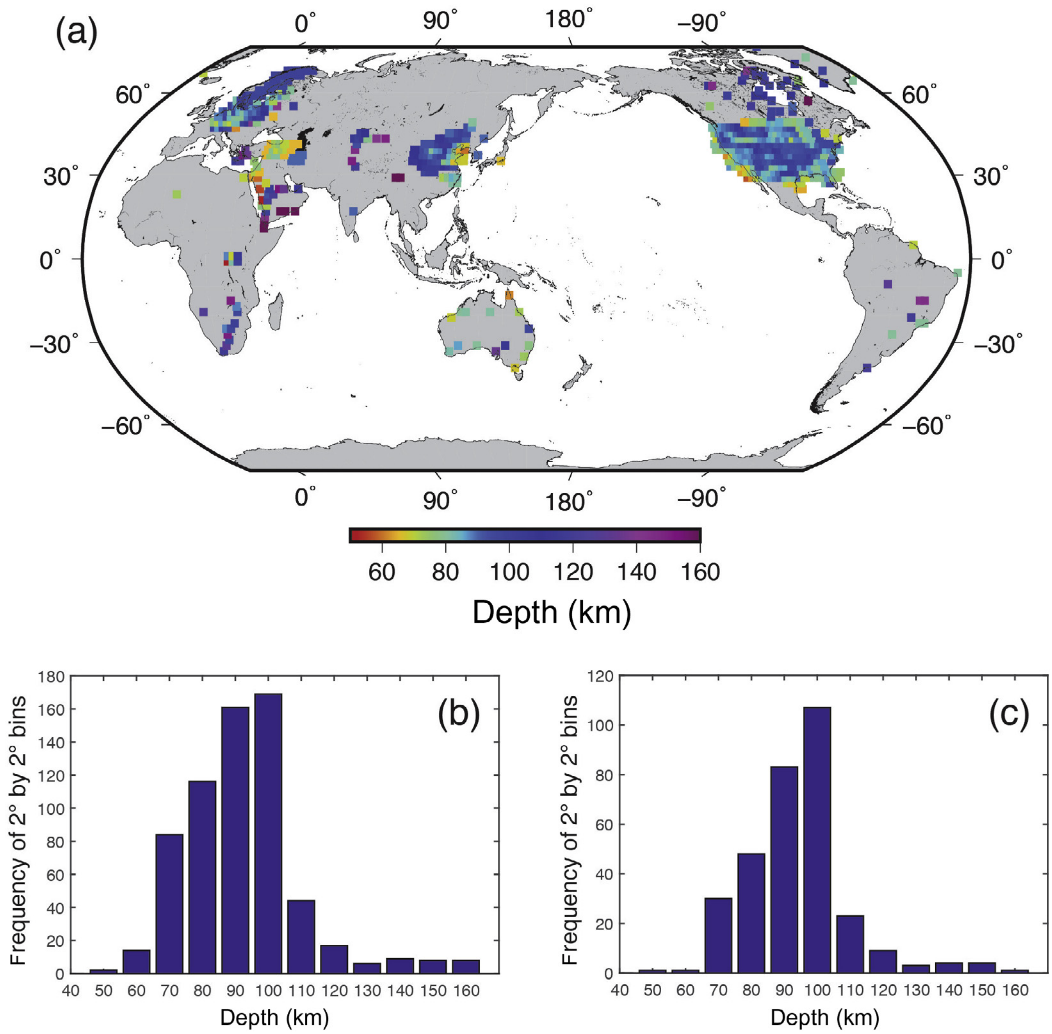

Fig. 1. Depths to the discontinuity with a downward velocity decrease in the shallow upper mantle (≤160 km) beneath continents. Observations are from teleseismic converted wave studies, referenced in [5,6], and recent teleseismic converted wave studies, including [7–9] for eastern China, [10] for North America, and [11] for northwestern Europe. (a) Geographic distribution of discontinuity depths. Data are averaged into 2° × 2°bins to avoid geographic sampling biases. Color indicates depth; (b) spatial frequency of observed depths shown in (a). Histogram bins are 10 km; (c) same as (b) but only for depths of the mid-lithosphere discontinuity (MLD) beneath cratons.

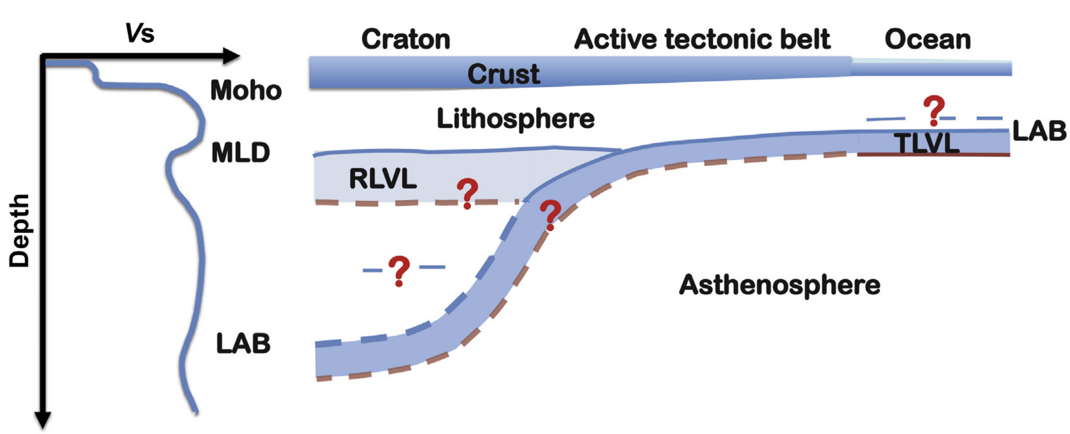

Fig. 2. A schematic of a shear velocity (*Vs*) profile showing the relative depths of the mid-lithosphere discontinuity (MLD) and the lithosphere-asthenosphere boundary (LAB) beneath continents and oceans. Solid lines represent sharp discontinuities; dashed lines mark either weaker discontinuities or gradual transition zones, or discontinuity structures that have not been well constrained. Question marks indicate structures with largely unconstrained features. RLVL – relatively low velocity layer bounded on top by the MLD; TLVL – thin low velocity layer, a 10–25 km thick water- or melt-rich channel immediately below the oceanic LAB (e.g., [19–21]). Whether such a channel also exists beneath continental lithosphere is unclear.

MLD depths within the cratonic SCLM. For instance, the strong velocity drop at the MLD beneath the Slave craton is accompanied by a significant increase in electrical conductivity at similar depths, and corresponds well with the petrologic layering of the SCLM [22]. In some cratonic regions, such as North America [30,31], South Africa [14], and Australia [32], the presence of the MLD is at least partially due to a change in seismic anisotropy, suggesting regional layering of mantle deformation.

3. Origin of the MLD

An integration of the seismic structural features of the MLD with other geophysical observations and geological, petrographic and geochemical data offer the opportunity to investigate the nature and origin of this discontinuity and the mechanism responsible for the layering of the SCLM. Several models or scenarios have been put forth:

(1) Partial melts or fluids. It has been suggested that the MLD is due to the presence of melts or fluids within the thick cratonic lithosphere (e.g., [26]). However, this model cannot explain the globally detected cratonic MLD, for it is inconsistent with magnetotelluric measurements of resistivity [23]. Furthermore, the inferred temperatures in most MLD locales (<1000 °C) are well below the solidus even with volatile-rich compositions [33].

(2) Elastically accommodated grain-boundary sliding. This model also involves thermal effects but mainly considers seismic velocity reduction during the transition from elastic to anelastic behavior of mantle mineral aggregates with the increase of temperature (e.g., [33]). While this model may explain the occurrence of the MLD at 900 °C and above, its validity has not been modeled for that below 900 °C [33]. Whether this mechanism can produce a large enough velocity decrease as that observed at the MLD is also debated [23].

(3) Compositional layering. The cratonic MLD is either interpreted as a remnant fabric inherited from the Archean formation of cratons, e.g., through lithospheric root accretion by underthrusting or thickening (e.g., [22,34]), or is suggested to result from later magmatic-metasomatic refertilization of the cratonic lithosphere (e.g., [35]). In both scenarios, accumulations of hydrous (e.g., phlogopite, amphibole) or other volatile-rich minerals (e.g., pyroxenes, carbonates) at MLD depths could be responsible for the velocity reduction (and in some cases an increase in electric conductivity) at the MLD. It is however still uncertain which mineral (or minerals) is the most plausible candidate (e.g., [6,23,35]). The application of this model to a global scale is also challenged by the lack of evidence for a large amount of hydrous minerals in mantle xenoliths [36].

(4) Layered deformation. Recent observations of layering in seismic anisotropy in the cratonic SCLM (e.g., [14,30–32]) are thought to represent a change in deformation fabric or deformation geometry with depth. This model, not mutually exclusive with the compositional layering model, also has problems to be a global explanation for the MLD. Given the complexity and spatial variability of seismic anisotropy structure in the SCLM, it is unreasonable that a change in anisotropy and hence deformation pattern can take place at ∼70–100 km depth beneath most, if not all, cratonic regions with distinctly different evolutions.

No matter which model is the most plausible, the commonly observed MLD beneath cratons may represent either a boundary separating two lithospheric layers that have formed in different tectonic regimes, possibly in different geological eras, or the top boundary of the lower lithosphere that has been considerably altered during the long-term evolution, or both. Consequently, the MLD and associated layering of the SCLM provide valuable clues to the formation and evolution of the continents.

4. Important issues and future studies

The widespread presence of the MLD in cratonic regions raises important issues. First of all, the nature and origin of the MLD itself is closely associated with the process of generating a thick, buoyant and strong cratonic root in the Archean time, and with the long-term evolution and modification of the SCLM. The presence of the MLD at ∼70–100 km depth (Fig. 1a and c) in regions of various tectonic evolutions histories indicates that ancient cratons may share common features in their formation and/or evolution. A comprehensive understanding of this issue requires detailed structural information of the MLD and SCLM and integration of multidisciplinary observations.

Secondly, the observation that the cratonic MLD and the LAB in tectonically active regions are comparable in terms of both depth and sharpness might reflect a genetic relationship between the two discontinuities. It has been proposed that the MLD beneath a craton may be the site of a future, shallower LAB after severe lithosphere rejuvenation [7,35], or that the MLD may represent a remnant of the LAB when the lithosphere was active and young [6]. In the latter model, the ancient LAB was thought to have developed in a similar way as the LAB in presently active regions and then deepened with time as the lithosphere cooled [6]. While the former model awaits verification with geodynamic simulations, the latter is questionable, as the present-day thick cratonic root in most cases could not have developed simply by progressive cooling and thickening from a thin lithosphere (e.g., [34]). One possibility is that the lithosphere may have thickened from the ancient shallow LAB by the accretion of a highly melt-depleted, buoyant, and viscous boundary layer produced by plume melting, as proposed for some continental regions with significant plume impactions in the Phanerozoic time (e.g., [37]). Again, whether this is a reasonable explanation for the global coincidence of the depths of the cratonic MLD and the LAB in active regions remain unknown. Indeed, investigating the relationship between the two discontinuities is helpful for gaining insights into not only the origin and evolution of cratonic lithosphere but also the tectonic processes and nature of the LAB in young, tectonically active regions.

Thirdly, the MLD and the underlying (relatively) low velocity layer may indicate a mechanically weak layer within the overall strong cratonic SCLM. A question then arises as to how such a weak layer in the SCLM could have affected the ensuing evolution of cratons? This weak layer may act as the focus of ductile deformation at mantle depths, playing a similar role as the pre-existing laterally weak belts that are expected to be areas of intense heating and strain concentration in the continental lithosphere during tectono-thermal events (e.g., [38]). Indeed, ductile deformation at the MLD depths within the SCLM has been invoked to explain the nucleation of some mantle earthquakes beneath continents [39], and has been proven to be capable of leading to delamination of the lower lithospheric mantle under compression regime [40]. On the other hand, geodynamic modeling indicates that the weak layer does not play a dominant role in craton destruction during lithospheric extension processes [41]. The common presence of the MLD beneath stable cratons also suggests that it might not have significantly affected on the long-term stability of cratons [7]. However, detailed investigations of this mantle weak layer in various real tectonic settings (e.g., subduction, collision, mantle plume, etc.) and in areas with or without a weak lower crust are necessary in understanding of the potential roles of vertical lithospheric layering in continental evolution.

Finally, and most importantly, our current understanding of the structure of the MLD and the SCLM is limited, and maybe even biased, by the non-ideal coverage of data and limitations of study methods. For example, the three-dimensional nature of the Earth's structure, being insufficiently accounted for in mapping discontinuities, may cause errors in the MLD depth on the order of 10–15 km (e.g., [7,23]). In many cases, the sharpness of the MLD and other lithospheric discontinuities were constrained by modeling seismic waveforms with fixed frequency contents (e.g., [14,23,28]), which may suffer from a trade-off between the magnitude of velocity reduction and thickness of the discontinuity. This, together with the complexity of real structures, might explain the discrepancies among MLD studies. Moreover, much less information has been gained about the structure of the low velocity layer below the MLD, including its thickness, the magnitude of seismic velocity decrease within this layer, and the sharpness of its bottom boundary compared to the MLD. Additional velocity discontinuities or layers were also recently found within or immediately below the lithosphere in some continental (e.g., [10,31,42]) and oceanic regions (e.g., [19–21]) (Fig. 2). Whether these discontinuities or layers are global phenomena or not is still a subject of speculation. It is also unclear whether or not the depths and sharpness of these discontinuities and the MLD are mutually dependent, and how the discontinuity structures are related to the regional evolution history or present-day tectonic setting. Structural information of all the discontinuities and related issues could fundamentally alter our understanding of the nature and behavior of the lithosphere, and how plate tectonics work beneath continents and oceans.

Overall, many issues remain about lithospheric discontinuities and the layering of the SCLM, and their association with continental evolution, which are increasingly receiving attention and have become frontier subjects in the Earth sciences (e.g., [12,23,33,35]). Tackling these issues will require improved constraints on the structures at depth from multidisciplinary observations and incorporation of all the constraints from laboratory experiments and geodynamical modeling.

Conflict of interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.scib.2017.06.003.

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