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978-0-521-84396-6 - The Lithosphere: An Interdisciplinary Approach
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1 What is the lithosphere?

> *"Unfortunately, the term lithosphere has recently been applied to many other concepts. The term is now in use with widely different meanings and implications."*
>
> *D. L. Anderson (1995)*

> *"How wonderful that we have met with a paradox. Now we have some hope of making progress."*
>
> *Niels Bohr*

The lithosphere forms the outer (typically, 50–300 km thick) rigid shell of the Earth. It includes the crust and, in general, some non-convecting part of the upper mantle called the lithospheric mantle (Fig. 1.1). Oceanic lithosphere is recycled into the mantle on a 200 Ma scale, whereas the study of the continental lithosphere is of particular importance since it offers the only possibility of unraveling the tectonic and geologic history of the Earth over the past *c.* 4 Ga. Knowledge of the structure, composition, and secular evolution of the lithosphere is crucial for the understanding of the geological evolution of the Earth since its accretion, including understanding the processes behind the formation of the early lithosphere, the processes behind plate tectonics, and lithosphere–mantle interaction. Many of these processes are closely linked to processes in the deep Earth and its secular cooling. Human society is strongly dependent on knowledge of the geodynamic processes in the lithosphere which manifest themselves as variations in topography and bathymetry, deposition of minerals many of which occur only in specific lithospheric settings, and high-impact geologic hazards. Understanding processes in the deep Earth is impossible without knowledge of lithosphere structure.

The specifics of the study of the Earth's deep interior, including the lithosphere, is that all of the parameters measured in direct and indirect geophysical and geochemical surveys are interrelated, being strongly dependent (among other factors) on pressure, temperature, composition, and the physical state of matter. This necessitates joint interpretation of the entire set of data provided using different techniques in the Earth sciences (such as seismic, gravity, thermal, electromagnetic, and petrological). Unfortunately, the true multidisciplinarity of lithosphere research has led to a situation where numerous, and often significantly different, lithosphere definitions have emerged from different geotechniques (Fig. 1.2). This chapter makes an "inventory" and "systematizes" the definitions of the lithosphere and their relations between each other and with similar concepts.

1.1 Historical note

The early gravity studies of the eighteenth and nineteenth centuries gave birth to the first, empirically based concept of a solid, non-deformable outer layer of the Earth overlying a

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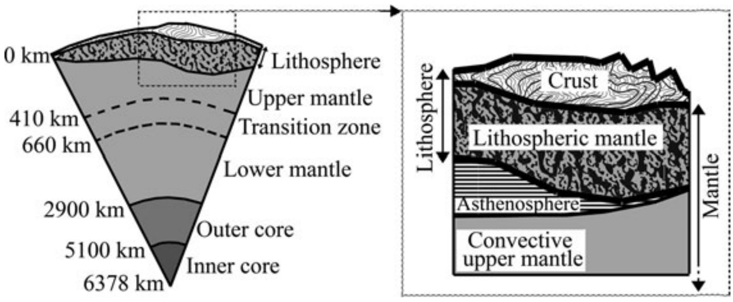

Fig. 1.1 Schematic Earth section showing various layers, not to scale (left). Zoom on the lithosphere (right).

Fig. 1.2 Confusion with various and numerous lithosphere definitions sometimes results in comparison of dissimilar parameters.

fluid, deformable interior. The thickness of this rigid layer, which supports sedimentary loads, was calculated from an analysis of gravity anomalies providing a value of about 100 km. Historically, the term "lithosphere" (from the Greek word meaning "rocky") appeared in geological literature probably only in the late nineteenth to early twentieth century. The first use of the term apparently dates back to the publication of J. Dana (1896), where in contrast to hydrosphere the solid Earth was described as "lithosphere". Soon afterwards, Barrel (1914) introduced the term "asthenosphere" to describe a fluid, deformable layer (estimated to be several hundred kilometers thick) below the "lithosphere".

The booming development of seismological methods in the first half of the twentieth century resulted in the discovery of the seismic low-velocity zone, the LVZ, in the Earth's mantle "centered at 100–150 km depth" (Gutenberg, 1954) with its base, the Lehmann discontinuity, determined to be at *c.* 220 km depth (Lehmann, 1961, 1962). [The existence of the Lehmann discontinuity had apparently been proposed almost a half-century earlier by the Russian Prince Boris Golitsyn (Galitzin, 1917), one of the founders of seismology and the inventor (1906) of the first electromagnetic seismograph.] Amazingly, the top of the seismic LVZ was at approximately the same depth as the transition between the solid outer layer of the Earth (the "lithosphere") and its low-viscous, deformable interior (the "asthenosphere"), as determined in early isostatic gravity studies. It was tempting to explain both gravity and seismic observations using the same physical mechanism, and the term "lithosphere" attained a new, seismic justification.

In the 1950s geothermics developed as an independent technique to assess the physical state of the deep Earth's interior. Although the first measurements of terrestrial heat flow were initiated by Everett (1883), the first reliable measurements only appeared in the late 1930s for the continents and a decade later for the oceans (Benfield, 1939; Bullard, 1939; Krige, 1939; Revelle and Maxwell, 1952). Data on surface heat flow allowed the calculation of crustal and upper mantle geotherms for a large range of continental and oceanic regions (e.g. Jaeger, 1965; McKenzie, 1967). These geotherms, combined with experimental and theoretical studies of melting conditions in the upper mantle (Uffen, 1952; Ito and Kennedy, 1967; Kushiro *et al.*, 1968), were used to explain the seismic LVZ in terms of peridotite partial melting. Thus, the term "lithosphere" obtained one more interpretation. It was an important step forward in upper mantle research because it linked observations, that came from independent fields of geophysics, into a joint picture of the physical state of the upper mantle.

Further development of geophysical techniques and a continuing accumulation of extensive geophysical (seismic, thermal, electromagnetic, gravity, and rheological) and geochemical data sets and models have led to much controversy in the use of the term "lithosphere", which had gradually become a convenient and widely used concept in geosciences. A drawback of the popularity of the term is that, depending on the geophysical techniques employed and physical properties measured, the lithosphere has different practical definitions. This has led to the situation where the "lithosphere" was stated to have "become an unnecessarily confusing concept" (Anderson, 1995) due to its excessive number of meanings. On the positive side, however, most lithosphere definitions are based on a pronounced change in the temperature-dependent physical properties of the upper mantle that occur at the transition from conductive (and rheologically strong) to convecting (and rheologically weak) upper mantle. They are supported by laboratory measurements of density, elastic moduli, and electrical conductivity of mantle rocks, parameters that have a strong temperature-dependence and a sharp change in properties at temperatures close to solidus (Murase and Fukuyama, 1980; Sato *et al.*, 1989; Constable *et al.*, 1992). A crucial dependence of most lithosphere definitions on the thermal regime of the upper mantle provides physical grounds for their direct comparison. Various lithosphere definitions are discussed in detail in the following sections.

1.2 Lithosphere definitions

1.2.1 Defining the lithospheric base

The lithosphere, as introduced at the beginning, is the outer layer of the Earth which includes the crust and, in general, the lithospheric mantle (Fig. 1.1). While the top of the lithosphere,

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obviously, coincides with the topographic surface, it is not an easy task to define the lithospheric base. The multiplicity of the existing practical definitions of the lithospheric base is related to:

- highly heterogeneous (both laterally and vertically) lithosphere structure;
- multiplicity of (geo)physical and (geo)chemical parameters by which it can be defined;
- multiplicity of methods that can measure these parameters;
- transitional (diffuse) nature of the lithospheric base;
- dualism in the lithosphere nature with respect to deep, global, and plate tectonic processes.

Changes in physical properties of mantle rocks measured in indirect geophysical surveys provide the basis for various definitions of the base of the lithosphere. The existing "lithosphere" definitions differ significantly, depending on the parameter under consideration. Furthermore, even the same parameter (for example, seismic velocity) will be measured with a significantly different resolution by different seismic techniques; physical assumptions and mathematical simplifications used in data interpretations often lead to significantly different practical "definitions" of the lithospheric base. For example, the thickness of seismic lithosphere constrained by seismic tomography can be biased by the choice of regularization procedure (smoothing of amplitudes versus gradients of velocity anomalies), the choice of the reference model, and by interpretations in terms of relative versus absolute velocity perturbations.

Most properties of the upper mantle change gradually with depth and do not exhibit sharp, "knife-cut", boundaries that could be uniquely associated with the lithospheric base. For this reason, the lithosphere–asthenosphere boundary (LAB) has a diffuse nature and, regardless of the definition employed, is always a transition zone over which a gradual change in physical and chemical characteristics occurs. As a result, the lithosphere thickness (the depth to the LAB) can be significantly different even for the same model of physical parameter variation with depth. The choice of a 1% or 2% velocity perturbation in a seismic model as the lithospheric base may lead to a ~50–100 km difference in the LAB depth (see Fig. 3.120). Similarly, defining the base of the mechanical lithosphere by the critical value of strength, strain rate, or viscosity leads to a large difference in the estimates of LAB depth (see Fig. 8.34).

The LAB is an important global boundary that has a dual nature, since it reflects the processes related to both global evolution (such as global mantle differentiation which led to crustal and lithosphere extraction; secular cooling of the Earth; styles and patterns of global mantle convection) and plate tectonics (such as lithosphere generation, recycling and modification by plate tectonics processes and secondary mantle convection) (Fig. 1.3). The duality in the nature of the lithosphere–asthenosphere boundary leads to significant differences in the LAB definitions from the "bottom" and from the "top". These definitions are discussed in detail in the corresponding chapters (see Sections 3.3.2; 3.6; 4.4.3; 5.1.2; 5.2.3–5.2.4; 6.1.4–6.1.5; 7.6; 8.1.3; 8.2.2); the correlations between some of them are shown in Fig. 1.4.

Four definitions of the lithosphere, *elastic, thermal, electrical, and seismic*, are widely used in geophysical studies. As is clear from their names, they are based on indirect

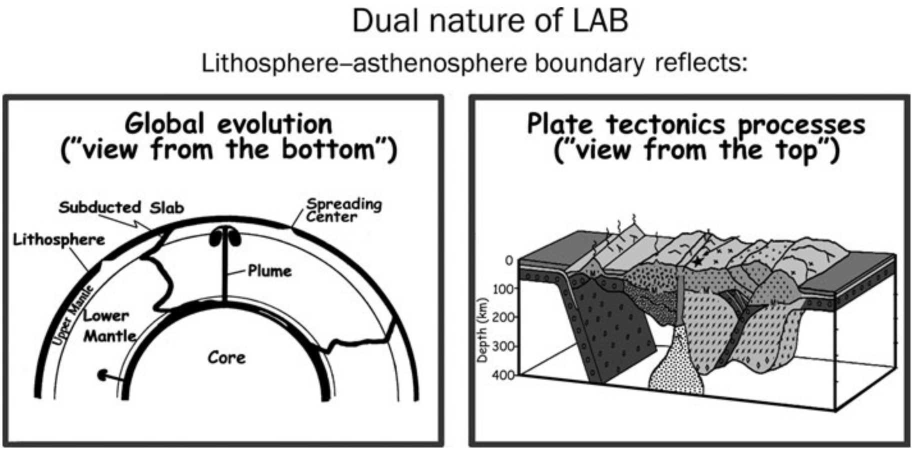

Fig. 1.3 Sketch illustrating the dual nature of the lithosphere–asthenosphere boundary (LAB). The LAB is an important global boundary that reflects the processes related to global evolution (mantle differentiation, secular cooling, global mantle convection, etc.) and to plate tectonics (the Wilson cycle, small-scale mantle convection, etc.). This duality causes difference in LAB definitions from the "top" and from the "bottom".

measurements of different properties of upper mantle rocks and thus they may refer to outer layers of the Earth of significantly different thickness. Petrologic studies of mantle xenoliths and interpretations of geophysical data in terms of chemical variations in the upper mantle provide additional definition of the *petrologic lithosphere*.

1.2.2 Elastic lithosphere

The concept of *elastic (flexural) lithosphere* (an elastic plate overlying viscous mantle) is close to the "classical" definition of the lithosphere as the upper rigid layer that moves mechanically coherently with plate motion (Barrell, 1914). The elastic thickness of the lithosphere is a measure of the mechanical strength of an elastic plate and it considers the lithosphere as a rheologically strong layer that provides the isostatic response of the plate to topographic and/or subsurface loads (i.e. due to variations in crustal thickness and density) and mechanically supports elastic stresses induced by lithospheric bending (flexure). In practice, the elastic thickness of the lithosphere is determined from the correlation between the topography and gravity anomalies (Fig. 1.5).

Although the concept of elastic lithosphere is related to the mechanical strength of the plate, the relationship between the two characteristics is not straightforward, and depends on lithosphere rheology, temperature, strain rate, and plate curvature. The mechanical thickness of the lithosphere (which can be defined as the depth where the yield stress becomes less than a particular limiting value) is, in general, greater than the thickness of the load-bearing lithospheric layer (the "elastic core") and the two parameters are only equal when the whole

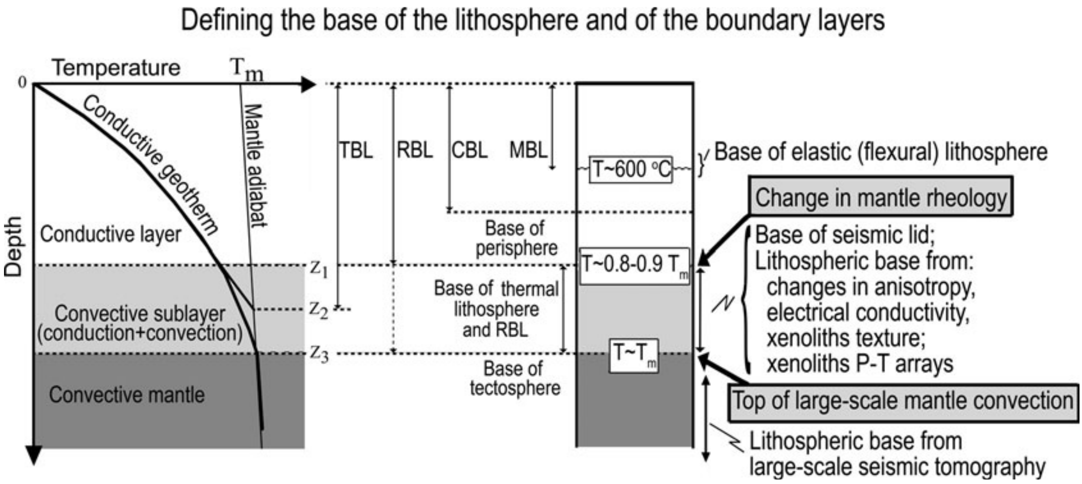

Fig. 1.4 Sketch illustrating relations between the conductive boundary layer and the convective mantle, on one side, and various approaches to define the base of the lithosphere, on the other side. The layer above depth Z_1 has a purely conductive heat transfer; in the transitional "convective boundary layer" between depths Z_1 and Z_3 the heat transfer mechanism gradually changes from convection to conduction. The base of the conductive boundary layer (or TBL) is between depths Z_1 and Z_3. Z_2 corresponds to the depth where a linear downward continuation of the geotherm intersects with mantle adiabat T_m that is representative of the convective mantle temperature profile. Thermal models commonly estimate Z_2, while large-scale seismic tomography images Z_3. The difference between Z_2 and Z_3 can be as large as 50 km, leading to a significant systematic difference in lithosphere thickness estimates based on seismic tomography and thermal data. Most practical definitions (except for chemical boundary layer and perisphere) are based on temperature-dependent physical properties of mantle rocks, and many lithosphere definitions correspond to the depth where a dramatic change in mantle rheology (viscosity) occurs. Layers RBL, TBL, CBL, and MBL are rheological, thermal, chemical, and mechanical boundary layers. Vertical dimensions are not to scale.

lithosphere thickness supports the load, such as in case of flexure of a single-layer elastic lithospheric plate (Sections 8.1.3 and 8.2.2).

The definition of an elastic (flexural) lithosphere implies that the lithosphere has elastic rheology and thus, from a rheological point of view, the base of the elastic lithosphere, in its simplest interpretation, corresponds to the elastic–plastic transition (Bodine *et al.*, 1981). The latter occurs at temperatures ranging from 250–450 °C for crustal rocks to 600–750 °C for upper mantle rocks (e.g. Meissner and Strehlau, 1982; Chen and Molnar, 1983). Thus the thickness of the elastic lithosphere is approximately one half those of the thermal, seismic, and electrical lithospheres, the bases of which are effectively controlled by lithospheric temperatures close to mantle adiabat (or to mantle solidus) (Fig. 1.4).[1]

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[1] In a multicomponent geochemical system such as the Earth's mantle, the constituting minerals have different melting temperatures. Solidus temperature corresponds to the temperature when melting of the most fusible component starts, while at liquidus temperature all minerals, including the most refractory, are molten. Between the liquidus and solidus temperatures, the material consists of both solid and liquid phases.

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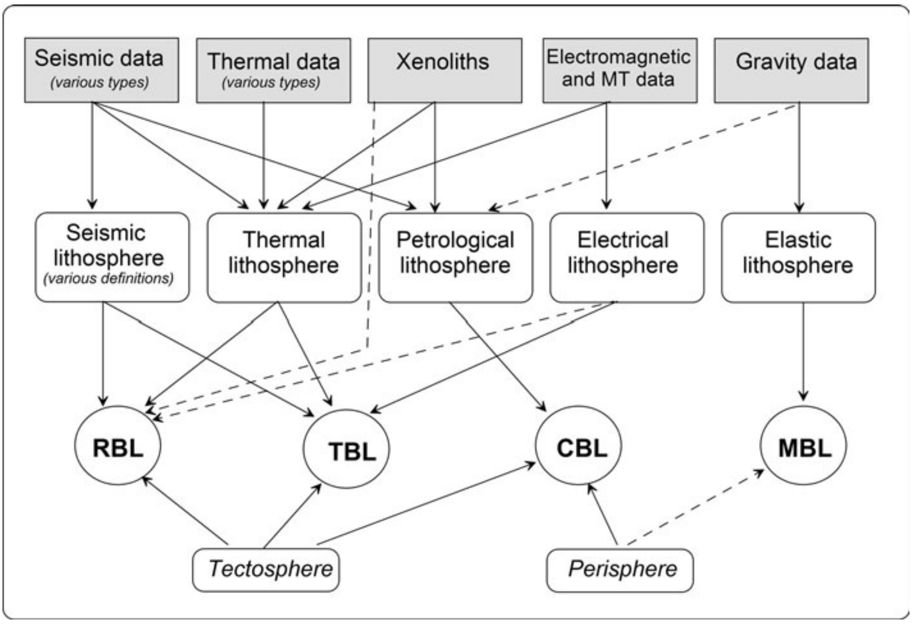

Fig. 1.5 Correspondence between different lithosphere definitions and links with other related definitions. RBL, TBL, CBL, and MBL are rheological, thermal, chemical, and mechanical boundary layers. See discussion in text.

1.2.3 Thermal lithosphere

Most practical geophysical definitions of the base of the lithosphere are based on temperature-dependent physical properties of mantle rocks measured indirectly in geophysical surveys (Fig. 1.5). From this point of view, the definition of the *thermal lithosphere (or TBL* – the layer with dominating conductive heat transfer above the convecting mantle) is the most straightforward and the least ambiguous. The base of the thermal lithosphere is commonly defined either by the depth to a constant isotherm (e.g. 1300 °C), or by the depth where a linear downward continuation of the geotherm reaches some pre-defined fraction of the ambient mantle temperature or mantle solidus (Fig. 1.4). The choice of ~0.8–0.9 times the mantle solidus (Pollack and Chapman, 1977) is supported by laboratory studies of physical properties of mantle rocks at high P–T conditions which indicate a sharp change in rheology and elastic properties of olivine-rich rocks at temperatures ~0.85–1.0 times that of solidus temperature (e.g. Sato and Sacks, 1989; Sacks *et al.*, 1989). The choice of mantle temperature 0.9–1.0 times that of the adiabatically upwelling mantle as the base of the thermal lithosphere is the most common; the potential temperature of the mantle is usually assumed to be in the range 1250–1350 °C since higher potential temperatures (1400–1450 °C) are inconsistent with laboratory data on P–T conditions at the 410 km depth (Katsura *et al.*, 2004).[2]

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[2] The potential temperature is the temperature of the mantle if it were decompressed adiabatically to the surface.

In practice, lithospheric geotherms are constrained by surface heat flow, from pressure–temperature equilibrium conditions of mantle mineral phases constrained by xenolith data (xenolith geotherms), or from conversions of seismic velocities into temperatures (see Chapters 4–5). For example, in stable continental regions, where thermal equilibrium has been established since the last major thermo-tectonic event, lithospheric geotherms can be calculated from solution of the steady-state conductivity equation constrained by surface heat flow measurements assuming that the depth distribution of heat producing elements is known. However, the approach is invalid for tectonically active regions, where non-steady-state thermo-dynamical models should be used to calculate the lithospheric geotherms (strictly speaking, heat transfer in the cratonic lithosphere also is not steady state because the time-scale of radioactive decay for major heat producing elements is comparable with the time-scale of thermal diffusion through the thick continental lithosphere, Michaut and Jaupart, 2004).

Boyd (1973) proposed the use of mantle-derived xenoliths to constrain lithospheric geotherms (xenolith P–T arrays) and thus to estimate the lithospheric thermal thickness (Fig. 1.5). This approach is based on the calculation of equilibrium P–T conditions for different mineral systems. Owing to a significant discrepancy between mantle pressures and temperatures constrained by different sets of geothermobarometers (sometimes reaching ±10 kBar and ±100 °C for the same rock samples, Grutter and Moore, 2003), the thickness of the thermal lithosphere based on xenolith P–T arrays is constrained non-uniquely and its value should not necessarily agree with lithospheric thickness constrained by heat flow data.

A strong temperature-dependence of elastic and non-elastic behavior of mantle rocks at high P–T conditions (e.g. Duffy and Anderson, 1989; Jackson *et al.*, 1990; Karato, 1993; Karato and Spetzler, 1990) provides the basis for conversions of seismic velocities to upper mantle temperatures, and thus allows for independent estimates of the thickness of the thermal lithosphere (Fig. 1.5). Most of the recent models of this type take into account frequency-dependent anelastic effects (dissipation) (Karato, 1993; Faul and Jackson, 2005). However, large uncertainty remains with taking into account the effects of partial melt (which strongly depend on melt geometry and water presence), fluids, seismic anisotropy, and compositional variations on seismic velocities (e.g. Popp and Kern, 1993; Sobolev *et al.*, 1996; Deschamps *et al.*, 2002; McKenzie *et al.*, 2005). Furthermore, velocity–temperature conversions can lead to physically meaningless solutions with extremely short-wavelength contrasts in mantle temperatures: while seismic velocities that form the basis for velocity–temperature conversions can exhibit a sharp velocity contrast between two adjacent lithospheric blocks, horizontal heat transfer that has a smearing effect on lithospheric temperatures should reduce short-wavelength temperature contrasts. Despite model limitations, velocity–temperature conversions have been applied to high-resolution regional seismic tomography and seismic refraction models to estimate lithospheric temperatures in most continents (Chapter 5). These studies provide useful constraints on lithospheric geotherms and the depth to thermal LAB.

1.2.4 Seismic lithosphere

Changes in elastic and non-elastic properties of mantle rocks measured in indirect seismological studies provide the basis for definitions of the base of the seismic lithosphere.

"Seismic lithosphere" is one of the most diverse categories of lithosphere definitions (Chapter 3). According to the classical definition, the *seismic lithosphere*, or the lid, is a seismic high-velocity layer above the low-velocity zone (LVZ) or above a zone of high velocity gradient in the upper mantle, presumably caused by partial melting. Other mechanisms (high-temperature relaxation, contrast in volatile content or in grain size) can also explain the origin of the LVZ and imply that the base of the lid is diffuse and extends in depth over some tens of kilometers.

Interpretations of mantle layers with a negative seismic velocity contrast in terms of the lithospheric base require a word of caution. When seismic models are constrained in relative instead of absolute velocities (i.e. as a velocity perturbation with respect to a reference model), the seismic LVZ may be an artifact of the reference model. This is the case, in particular, when the PREM (preliminary reference Earth model) model (with a sharp velocity increase at 220 km depth, typical for the oceanic lithosphere, but not required by seismic data for the continental regions) is used as a reference model for stable continents (Kennett, 2006; Fig. 3.85). Another confusion arising from the definition of the seismic lid is related to the fact that LVZ can be produced without involving mantle melting: a velocity decrease with depth may happen when the seismic velocity increase due to pressure increase is less than the velocity decrease due to temperature increase with depth.

High-temperature laboratory measurements of density and elastic moduli of mantle rocks that indicate a sharp change in seismic velocities and seismic attenuation at temperatures close to mantle solidus provide the basis for interpretations of elastic and non-elastic mantle tomography in terms of lithospheric thickness. In such approaches, the seismic LAB is identified with a (to some extent, arbitrary) critical value of seismic velocity or attenuation. It is important to remember that the existence of the transitional layer in the mantle, where the mode of heat transfer gradually changes from conduction to convection, leads to a significant difference in lithospheric thickness constrained "from the top" and "from the bottom" (Fig. 1.4). Large-scale tomography models, which are sensitive to velocity anomalies associated with the convective mantle, treat the base of the lithosphere as the top of a large-scale mantle convection (Sleep, 2003). Thus, the lithospheric thickness estimated from large-scale seismic tomography models may extend some tens of kilometers deeper than the thermal lithosphere (or TBL).

If the seismic velocity decrease with depth is associated with a sharp decrease in upper mantle viscosity (e.g. due to the presence of partial melt), the lithospheric base should be a rheological boundary. Asthenospheric flow and shear in the rheologically weak layer below the lithosphere may produce alignment of minerals, including highly anisotropic olivine. As a result, the depth at which the axis of anisotropy changes orientation from fossil, frozen-in anisotropy typical of the lithospheric mantle to the anisotropy pattern related to the present plate motions and mantle flow typical for the asthenosphere (convective mantle) can also be considered as the base of the seismic lithosphere (Sections 3.1.5, 3.6.4). Similarly, a change in mantle anisotropy associated with the change in the mechanism of mantle deformation from dislocation creep to diffusion creep can be interpreted in terms of the seismic LAB, which in this case corresponds to the base of the rheological boundary layer.

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1.2.5 Electrical lithosphere

The *electrical lithosphere* is usually defined as the highly resistive upper layer above the highly conducting asthenosphere. Its base corresponds to a sharp change in mantle conductivity (resistivity) and is commonly explained by the presence of 1–3% melt fraction (although the presence of a high-conducting phase such as graphite may produce a similar effect). In many regions the depths to the top of the asthenospheric conductor and to the top of the seismic LVZ are well correlated. Similarly to seismic velocity–temperature conversions, the strong temperature-dependence of the electrical conductivity of olivine can be used to estimate regional geotherms from magnetotelluric field observations (Ledo and Jones, 2005).

Anisotropic diffusivity of hydrogen in olivine crystals produces direction-dependent electrical conductivity. Thus, if olivine is partially aligned by asthenospheric flow, the depth where a change in mantle electrical anisotropy is observed can be interpreted as the electrical LAB. Since asthenospheric flow also produces lattice-preferred orientation of olivine crystals leading to seismic anisotropy, a joint analysis of seismic and electrical anisotropy data can provide important constraints on asthenospheric flow at the lithospheric base and the base of the rheological boundary layer.

1.2.6 Petrologic lithosphere

Clearly the most straightforward way of defining the base of the petrologic lithosphere is provided by mantle-derived xenoliths. For example, the base of the petrologic lithosphere can be determined by the change from depleted (lithospheric) to undepleted (asthenospheric) composition. Numerous petrologic studies of xenoliths from the Archean–Proterozoic cratons of Africa (Kaapvaal, Zimbabwe, and Tanzania cratons), Siberia, Europe (Baltic Shield), Canada (Superior and Slave cratons), and South America (Guyana craton) indicate that the depth of the transition from depleted to undepleted mantle composition often coincides with the depth to the isotherm of *c*. 1200–1300 °C and thus is close to the depth where a continental conductive geotherm intersects the mantle adiabat. Thus, in some cratonic regions, the petrologic and thermal lithospheres may have similar thicknesses (Chapter 5). However, this is not necessarily the general case, since in many cratons the transition from depleted to non-depleted composition is gradual, and in some cratons (e.g. the Slave craton in northern Canada) the lithosphere has compositional layering. In some petrologic definitions (such as those based on Y-depleted garnet concentrations (Griffin and Ryan, 1995)), the base of the lithosphere is a strongly non-isothermal boundary with temperatures at the lithospheric base (strictly speaking, at the base of the CBL) ranging from 950 °C to 1250 °C over lateral distances of 100–200 km (Griffin *et al*., 1999a). These huge short-wavelength temperature variations at the base of the CBL preclude a physically meaningful comparison of the thus defined "petrological lithospheric thickness" with lithospheric thickness estimated by geophysical methods (e.g. seismic, magnetotelluric, Chapters 3, 7), in which the base of the lithosphere (or the LAB) is defined by a sharp change in temperature-dependent physical properties of the upper mantle. The base of the