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A comparison of lithospheric thickness models

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Abstract

The outermost layer of the solid Earth consists of relatively rigid plates whose horizontal motions are well described by the rules of plate tectonics. Yet, the thickness of these plates is poorly constrained, with different methods giving widely discrepant results. Here a recently developed procedure to derive lithospheric thickness from seismic tomography with a simple thermal model is discussed. Thickness is calibrated such that the average as a function of seafloor age matches the theoretical curve for half-space cooling. Using several recent tomography models, predicted thickness agrees quite well with what is expected from half-space cooling in many oceanic areas younger than ≈ 110 Myr. Thickness increases less strongly with age for older oceanic lithosphere, and is quite variable on continents, with thick lithosphere up to ≈ 250 km inferred for many cratons. Results are highly correlated for recent shear-wave tomography models. Also, comparison to previous approaches based on tomography shows that results remain mostly similar in pattern, although somewhat more variable in the mean value and amount of variation. Global correlations with and between lithosphere thicknesses inferred from receiver functions or heat flow are much lower. However, results inferred from tomography and elastic thickness are correlated highly, giving additional confidence in these patterns of thickness variations, and implying that tomographically inferred thickness may correlate with depth-integrated strength. Thermal scaling from seismic velocities to temperatures yields radial profiles that agree with half-space cooling over large parts

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of their depth range, in particular for averaged profiles for given lithosphere thickness ranges. However, strong deviations from half-space cooling profiles are found in thick continental lithosphere above depth ≈ 150 km, most likely due to compositional differences.

9 *Keywords:* lithosphere, tomography, half-space cooling, craton, elastic
10 thickness

11 **1. Introduction**

12 The theory of plate tectonics gives a good description of the kinematic behavior of the Earth's surface. Plate tectonics is the surface expression of convection
13 in the Earth's mantle, and in the last ~ 50 years since it was first formulated
14 (e.g., McKenzie and Parker, 1967; Morgan, 1968) a great deal of progress has
15 been made in understanding how a set of plates that are approximately rigid
16 but move relative to each other can arise as a consequence of mantle dynamics,
17 and how the tectonic plates interact with the underlying mantle.

18 Plates can experience drag as they move over the mantle beneath – which
19 is assumed to behave like a viscous fluid over geologic time scales. This is for
20 example the case, if a plate is mainly pulled by a subducted slab. But plates
21 can also be driven by convection currents in the underlying mantle (e.g., Becker
22 and O'Connell, 2001; Conrad and Lithgow-Bertelloni, 2002; Becker, 2006; van
23 Summeren et al., 2012). Both mechanisms of interaction strongly depend on
24 the thickness of the lithospheric plates: Thick lithospheric keels couple the
25 plates more strongly to the underlying mantle, in particular because below the
26 asthenosphere viscosity increases again with depth. Thicker lithosphere may
27 reach to depths where mantle viscosity is already higher again (e.g., Gurnis and
28 Torsvik, 1994; Zhong, 2001; Conrad and Lithgow-Bertelloni, 2006).

29 Hence knowledge of lithosphere thickness helps the understanding of plate-
30 mantle interactions. Further, distinguishing thermal and compositional litho-
31 sphere is important for, e.g., understanding different contributions to topogra-
32 phy (isostatic and dynamic). More generally, an understanding of lithosphere
33

34 thickness (both thermal and compositional) is important to address many ques-
35 tions in continental geodynamics.

36 We envision here the lithosphere as the outermost layer of the Earth that
37 moves more or less coherently as tectonic plates, due to its stronger rheology,
38 and higher viscosity in particular. Rheology relevant for lithosphere thickness
39 may be influenced by thermal and compositional effects (e.g., Lee et al., 2005),
40 and may change gradually with depth. The thickness of lithospheric plates
41 is therefore not sharply defined (with any specific definition being somewhat
42 arbitrary) and also rather poorly known. Furthermore strain rate is a possible
43 important contributor to influencing the depth of the lithosphere-asthenosphere
44 boundary (LAB), as rheology may be strain rate dependent. Therefore, there
45 may be a strain rate gradient across the LAB, with important feedbacks between
46 temperature, strain rate and rheology.

47 This current situation is not caused by a lack of information. There is a
48 wealth of information from which thickness can be indirectly inferred, but some
49 of these thickness estimates turn out to be rather different. In contrast to the
50 lateral extent of plates, which can be directly mapped (for example, based on
51 geodesy), there is no such direct way to determine their vertical extent.

52 Here, a new method of deriving radial mantle temperature profiles from seis-
53 mic tomography is introduced. This method is then used to derive lithosphere
54 thickness by assigning the base of the lithosphere to a temperature isosurface.
55 The rationale behind this approach is that temperature is probably the most im-
56 portant factor controlling lithosphere rheology, in particular viscosity, although
57 composition and strain rate also has an effect. And rheology is what deter-
58 mines the long-term behaviour of mantle materials, whether it is rigid enough
59 to move as a coherent plate, or soft enough to be easily sheared. In other con-
60 texts, other characteristics may be important, for example whether material has
61 elastic strength. This leads to a different definition of lithosphere thickness, as
62 material may be hot enough such that it has lost its elastic strength, but it
63 may still be rigid enough to not substantially deform on geologic timescales.
64 Here rather the latter is taken as what distinguishes the lithosphere from the

65 underlying mantle.

66 Deviations of the determined temperature profiles from those expected for
67 lithospheric cooling further allow to infer compositional variations. Then a
68 systematic comparison with other thickness estimates is performed. First, we
69 briefly recapitulate the different methods with their advantages and shortcomings.
70 If two methods give different results, it does not mean that one has to be
71 wrong; it can also be that different methods see different aspects of the litho-
72 sphere (e.g., Burov and Diament, 1995), for which there is no unique definition
73 (e.g., Eaton et al., 2009; Fischer et al., 2010). We shall first strive to constrain
74 the thermal lithosphere, and then comment on possible complexities due to
75 composition.

76 In the end, the aim in devising a new lithosphere thickness model is obviously
77 not to solve this issue. Rather, by comparing the new model to a variety of other
78 lithosphere thickness estimates, and comparing these other estimates among
79 each other, we would like to say something about which features of thickness
80 models can be regarded as robust, and where the major uncertainties are.

81 *1.1. Seismic Tomography*

82 Seismic tomography aims at determining v_P and v_S velocity distributions,
83 and the latter are typically better constrained than the former for the uppermost
84 mantle because of the predominant sensitivity of surface waves to v_S . Typically,
85 velocities are expressed in terms of anomalies, i.e. deviations from a global,
86 average reference model that depends on depth only. These deviations in turn
87 depend on temperature, pressure (i.e. depth), and composition and can be linked
88 readily to plate tectonics for the upper mantle (e.g., Zhang and Tanimoto, 1991;
89 Ritzwoller et al., 2004; Priestley and McKenzie, 2006; Lekic and Romanowicz,
90 2011; Burgos et al., 2014).

91 Compositional variations probably play an important role inside the litho-
92 spheric mantle (e.g., Jordan, 1978; Forte and Perry, 2000; Deschamps et al.,
93 2002; Griffin et al., 2009; Cammarano et al., 2011). In particular, continental
94 mid-lithosphere discontinuities (MLDs) (e.g., Selway et al., 2015; Rader et al.,

2015) may represent compositional layering (e.g., Yuan and Romanowicz, 2010).
Mid-lithospheric discontinuities may be common in oceanic lithosphere as well
(e.g., Beghein et al., 2014; Auer et al., 2015, and references therein). Beneath the
lithosphere, seismic velocity anomalies can perhaps serve better as a proxy for
temperature anomalies. However, due to partial melting and resulting variations
in volatile content and chemical composition, there could still be non-thermal
seismic velocity variations in the asthenosphere (e.g., Goes and van der Lee,
2002).

If one knows the dependence of seismic velocity anomalies on temperature
anomalies and depth, and the global average for the temperature versus depth
profile, one can in principle convert seismic anomalies to temperature. After
assigning a given temperature to the base of the lithosphere, it is then straight-
forward to derive a lithosphere thickness model.

However, there are difficulties with this approach. Firstly, it is not straight-
forward to derive the reference profile for temperature versus depth. Mainly,
the surface value is known, and approximately the value it approaches at depths
corresponding to the thickest lithosphere. Secondly, any compositional anoma-
lies inside the lithosphere will also affect the (global average) reference profile
of seismic anomalies. Hence, for example, zero seismic velocity anomaly outside
the lithosphere will not correspond to zero temperature anomaly and vice versa.
Determining this offset and its dependence on depth is not straightforward ei-
ther, but it probably overall decreases from a maximum value near the surface
to zero at greater depth. Apart from this offset the relation of seismic velocity
and temperature anomalies can in principle be determined from mineral physics.

Besides the more principal problems already mentioned, there are also more
practical issues: Tomographic inversions often need to be regularized such that
the amplitude of recovered seismic velocity anomalies may be less than in reality.
They are also affected by smearing: For example, if there is a negative seismic
anomaly due to a compositional anomaly inside the lithosphere, and a negative
anomaly due to high temperature outside, they may appear as one anomaly
due to smearing, hence it may not be possible to determine lithosphere thick-

ness properly. *S*-wave tomography models typically feature strongly positive anomalies to great depth beneath cratons where thick lithosphere is expected (e.g., Gung et al., 2003). Jordan and Paulson (2013) even suggest a thick tectosphere extending below 350 km depth after applying a smearing correction.

Another, smearing-related problem may occur near subduction zones, if there is a slab underlying the lithosphere but separated by a thin layer of asthenosphere which is not seen by tomography. In this case, lithosphere thickness may be over-estimated. Here, it is attempted to remove slab-related structures approximately by setting tomographic anomalies to zero near the slab contours of the RUM model (Gudmundsson and Sambridge, 1998), and smoothing sharp edges that are introduced by this procedure. This is a conservative estimate of the extent of subducted slabs possibly masking as thick overriding lithosphere, since RUM is based on major, seismically active regions only.

Additional factors that affect the different tomography models are the frequency content of the information used, the varying vertical resolution arising from different parametrizations, and the geographic resolution associated with available path coverage.

Steinberger (2016) implemented an approach of determining lithosphere thickness, and here, for the first time, the procedure and results will be discussed in detail. Essentially, the principal uncertainties are treated by leaving two free parameters that describe the maximum offset (due to compositional anomalies inside the lithosphere) and the length scale over which temperature approaches the adiabat and composition of sublithospheric mantle, and constrain these parameters by matching lithosphere thicknesses determined in the oceans with thicknesses inferred from seafloor ages. This match works quite well for some of the newer tomography models, as will be illustrated in the methods section.

The robustness of the new method will be shown by determining and comparing lithosphere thickness for several recent tomography models, by comparing with results where the lithosphere thickness is simply inferred from an isosurface of tomography, and by comparing with other recent tomography-based lithosphere thickness models (Figure 1), and show that they are all highly cor-

related, despite different procedures. Conrad and Lithgow-Bertelloni (2006) (Figure 1c), for example, use a constant seismic velocity anomaly for depth on continents, and infer thickness from seafloor age in the oceans. Bird et al. (2008) (Figure 1e) use the integrated anomaly over the top 400 km as a proxy for lithosphere thickness on the continents, and again age-dependent thickness in the oceans.

Priestley and McKenzie (2013) (Figure 1d) use a procedure similar to ours, but also constraints from mantle nodules in kimberlites on continents. The LITHO1.0 model of Pasyanos et al. (2014) (Figure 1f) is created by constructing an appropriate starting model and perturbing it to fit high-resolution surface wave dispersion maps (Love and Rayleigh, group and phase). Lithospheric thickness is then defined as the thickness of the high-velocity mantle layer underlying the crust and overlying a lower velocity layer (asthenosphere) that is required to fit the surface wave data. Studies based solely on fundamental mode surface waves start losing resolution around 250 km depth, so they are not optimally suited for determining the thickness of the lithosphere, as they tend to smear images in the vertical direction. This issue is addressed by models such as SAVANI (Auer et al., 2014) using both surface and body waves, and not just fundamental mode data, but also overtones. SL2013 (Schaeffer and Lebedev, 2013) also effectively uses overtones, giving improved vertical resolution.

We note that there are a number of other thermal (and sometimes also compositional) models inferred from seismic models or data in the literature which allow to estimate the thickness of the thermal lithosphere (e.g., Deschamps et al., 2002; Shapiro and Ritzwoller, 2004; Cammarano et al., 2011; Khan et al., 2011), but the aim here is to focus only on a few observational techniques (e.g. tomography vs. impedance-sensing receiver functions) and constraints (e.g. heat flow), and not consider joint modeling approaches for clarity.

1.2. Receiver functions

Figure 1a shows thickness from receiver functions, l_{RF} , from Rychert et al. (2010). Here the “cap version” is shown, where values are adopted from the

187 nearest data point up to five arc-degrees distance, but different interpolation
188 would yield similar results. The receiver function (RF) method is based on the
189 conversion from P - to S -waves or the other way round, and therefore images
190 rather sharp velocity contrasts. Hence what is interpreted as the base of the
191 lithosphere from RF is not necessarily the same thing physically as what other
192 methods such as tomography would imply (see, e.g., Eaton et al., 2009; Fischer
193 et al., 2010, for reviews). Interpretation of receiver function results in terms
194 of the bottom of the lithosphere is complicated by possibly widespread mid-
195 lithospheric discontinuities (e.g. Romanowicz, 2009; Selway et al., 2015).

196 1.3. Heat flow

197 Artemieva (2006) computed lithosphere thickness on continents from geotherms
198 constrained by reliable data on borehole heat flow measurements (l_T in Figure
199 1b). For comparison, also an inference from a global heat flow compilation
200 (Davies, 2013) is shown in Figure 1j. We here use the inverse of heat flow
201 q as a simple proxy, assuming that $1/q$ is proportional to lithosphere thick-
202 ness (as, e.g., for half-space cooling), for the sake of argument. The latter has
203 not been corrected for radiogenic heat in the crust, and we mainly show this
204 simple model for comparison with the Artemieva (2006) model, which tries to
205 account for crustal heat production, and for comparison with other models in
206 the oceans, where the Artemieva (2006) model is not defined. In the following
207 we will, among these two models, mainly focus on Artemieva (2006).

208 1.4. Elastic thickness

209 Audet and Bürgmann (2011) calculated estimates of the lithosphere’s effec-
210 tive elastic thickness over the continents from a comparison of the spectral coher-
211 ence between topography and gravity anomalies and the flexural response of an
212 equivalent elastic plate to loading (T_E in Figure 1g). The thickness over which
213 the plate reacts elastically is expected to be less than the thickness over which
214 temperature approaches the adiabat (i.e. thermal thickness) or holds equivalent

viscous “strength” (e.g., Burov and Diament, 1995; Watts, 2001). The estimation of elastic thickness depends on fitting in the wavenumber domain and the broad span of wavelengths needed is harder to achieve near continental margins compared to interiors, for example.

In addition to these methods, changes in anisotropy can also give information on lithosphere thickness (e.g., Gung et al., 2003; Debayle and Ricard, 2013; Burgos et al., 2014; Becker et al., 2014; Auer et al., 2015). However, interpretation is complicated and no global lithosphere thickness maps based on anisotropic structure have been published in recent years, although earlier studies (Babuška et al., 1998; Plomerová et al., 2002) and oceanic-only approaches (e.g. Burgos et al., 2014) exist. Hence the comparison will be limited to the four methods based on seismic tomography, heat flow, receiver functions and elastic thickness. Figure 1 shows that these results are already quite different from each other, and we proceed to assess these differences quantitatively.

2. Methods: Determining lithosphere thickness from seismic tomography

The base of the lithosphere is assigned to a given temperature T_L . Its depth is determined from five recent, shear wave tomography models (see Table 1), whereby additional layers may be introduced such that their spacing is at most 25 km. Above the uppermost layer of the original model, values are set equal to that layer; below they are interpolated. We follow these steps:

1. Relative seismic velocity anomalies, δv_S , are assumed to have a thermal component $\delta v_S/v_S|_{th}$ that is proportional to deviations of the actual temperature profile $T(z)$ from the reference profile $T_0(z)$ representing the global average:

$$\delta v_S/v_S|_{th} = -F_{th} \cdot \frac{T(z) - T_0(z)}{T_m - T_s} \quad (1)$$

where T_s is surface temperature and T_m (adiabatic) mantle temperature (Figure 2). F_{th} can be determined from $T_m - T_s$ (e.g., Herzberg et al., 2007) and the sensitivity of seismic velocity to temperature $(dv_S/dT)/v_S$ (e.g.,

Steinberger and Calderwood, 2006). With $T_m - T_s = 1325$ K, which is the difference between the mean value of the range $1280 - 1400^\circ\text{C}$ (Herzberg et al., 2007) and $T_s = 15^\circ\text{C}$, and $(dv_S/dT)/v_S = -1.5 \cdot 10^{-4}/\text{K}$, it follows $F_{th} = 19.9\%$. However, tomography models could be affected by damping, resulting in lower values of F_{th} . But this would also lead to an under-prediction of model topography amplitude (compared to residual topography), and since it is rather over-predicted (Steinberger, 2016), lower values of F_{th} will not be considered.

2. T_L is chosen such that

$$\frac{T_L - T_s}{T_m - T_s} = \text{erf}(1) = 0.843 \quad \text{or} \quad T_L = T_s + 0.843 \cdot (T_m - T_s) \quad (2)$$

following Sandwell (2001). This fraction 0.843 is arbitrary, since the thermal lithosphere boundary is probably not sharp if viscosity decreases continuously with temperature. Therefore also some results with fractions 0.9 and 0.78 will be shown to assess the variability arising from the choice of this fraction.

3. T_L can now be converted to a value $\delta v_S/v_S|_{th,L}$ of $\delta v_S/v_S|_{th}$ at the base of the lithosphere, using eq. (1).

$$\begin{aligned} \delta v_S/v_S|_{th,L} &= -F_{th} \cdot \frac{T_L - T_0(z)}{T_m - T_s} = \\ &= F_{th} \cdot \frac{T_m - T_L}{T_m - T_s} - F_{th} \cdot \frac{T_m - T_0(z)}{T_m - T_s} = 3.1\% - 19.9\% \cdot \frac{T_m - T_0(z)}{T_m - T_s} \end{aligned} \quad (3)$$

where eq. (2) has been used in the last equality.

However, the total relative seismic velocity anomaly at the base of the lithosphere $\delta v_S/v_S|_L$ also has a compositional component, and this is not due to compositional variations at the lithosphere boundary (it shall be assumed that all compositional variations occur inside the lithosphere, away from the boundary), but due to the (global average) reference value being affected by compositional variations inside the lithosphere. So eq. (3) can be modified to

$$\delta v_S/v_S|_L = F_{th} \cdot \frac{T_m - T_L}{T_m - T_s} - F_{th} \cdot \frac{T_m - T_0(z)}{T_m - T_s} + F_C \cdot C_0(z). \quad (4)$$

Introducing the term $F_C \cdot C_0(z)$ implies that the reference temperature profile does not correspond to the reference seismic profile, rather there is a depth-dependent offset due to compositional variations. The function on the right-hand side shall be called “cutoff function”, and lithosphere thickness shall be assigned depending on the value of the relative seismic velocity anomaly $\delta v_S/v_S$ in comparison to the cutoff function. The exact shape of the cutoff function is unknown, but some of its properties can be stated: The term $(T_m - T_0(z))/(T_m - T_s)$ is unity at the surface and approaches zero for large depth, and $C_0(z)$ should have the same properties, if F_C is the surface value of the compositional component. It therefore appears as a reasonable choice to use

$$\delta v_S/v_S|_L = F_{th} \cdot \frac{T_m - T_L}{T_m - T_s} - F_{tot} \cdot \left(1 - \operatorname{erf}\left(\frac{z}{z_0}\right)\right) \quad (5)$$

as cutoff function, as $1 - \operatorname{erf}(z/z_0)$ also has the value 1 for $z = 0$ and approaches zero for large z . This is for example the case if

$$(T_m - T_0(z))/(T_m - T_s) = C_0(z) = 1 - \operatorname{erf}(z/z_0) \quad (6)$$

and $F_{th} - F_c = F_{tot}$, but this is not a necessary condition. Eq. (6) does not imply that temperature follows an error function profile at every point. Rather, it is merely assumed that global mean temperature follows such a profile. z_0 and F_{tot} are two parameter that will be adjusted, as explained below. More generally, this corresponds outside the lithosphere to the equation

$$\delta v_S/v_S = F_{th} \cdot \frac{T_m - T(z)}{T_m - T_s} - F_{tot} \cdot \left(1 - \operatorname{erf}\left(\frac{z}{z_0}\right)\right). \quad (7)$$

Solving this equation for $T(z)$ apparent temperature profiles can be computed. Clear deviations from what appears a reasonable temperature profile can give indications on compositional variations, in particular if at other depth ranges the results agree with expectations.

For simplicity, we have assumed here a linear relation between temperature and velocity anomalies. However, the effect of temperature dependent attenuation on seismic velocities makes this relation non-linear (e.g. Cammarano et al.,

2003; Cammarano and Romanowicz, 2007). To assess the effect of this nonlin-
earity, we therefore also consider a case where a quadratic term $b \cdot (\text{erf}(z/z_0) -$
 $\text{erf}(1))^2$ has been added to the cutoff function eq. 5, corresponding to the next
term in the Taylor expansion. We choose a value $b = 21.9\%$, that approximately,
by visual comparison, corresponds to Fig. 3b of Cammarano et al. (2003). Also,
the cutoff function eq. 5 does not consider depth-dependence of F_{th} . To assess its
effect, additionally a case is considered where $F_{th} = 19.9\% \times \left(1 - \frac{4}{15} \frac{z-200 \text{ km}}{200 \text{ km}}\right)$
approximately corresponding to Steinberger and Calderwood (2006), and F_{tot}
has been modified accordingly, assuming $F_{tot} = F_{th} - F_c$ and F_c unchanged.
Lastly, also cases are considered where 0.843 has been replaced by 0.9 and 0.78,
respectively, in eq. 2 to assess the effect of assuming different temperatures for
the base of the lithosphere.

Bounds for the maximum value of lithosphere thickness (usually 400 km)
and its minimum (usually equal to crustal thickness from CRUST 1.0 (Laske
et al., 2013)) are prescribed. Our procedure then yields a unique lithosphere
thickness if there is exactly one depth such that $\delta v_S/v_S$ is greater than the
cutoff function above, and less below (see Figure 2 B). If there is more than one
depth where this is the case, then, for the oceanic regions, the shallowest one is
chosen. In this way, no detached slabs or blobs may be included as lithosphere,
as long as they are clearly imaged. In continental regions, cases of shallow low-
velocity anomalies (presumably due to compositional variations) underlain by
high-velocity anomalies, both within the lithosphere, may be common (Lekic
and Romanowicz, 2011) and are presumably physically plausible: Therefore, if
all options for lithosphere thickness are < 150 km, the largest one is assigned.
Only if at least one option is > 150 km, the smallest one of these is chosen. If
 $\delta v_S/v_S$ is smaller (resp. larger) than the cutoff function at all depths between
minimum and maximum, lithosphere thickness is set to the minimum (resp.
maximum). Where the uppermost layer of the tomography model is still in the
mantle, anomalies are set to taper linearly to zero from the uppermost layer at
depth 25 km or less.

For larger values of z_0 , the cutoff function, eq. (5) (Figure 2 B), is stretched in the vertical direction and thus shifted towards more negative values for a given depth, and vice versa. This means, more points will be assigned to the lithosphere, resulting in thicker lithosphere values. For larger values of F_{tot} , the cutoff function is also shifted to the left, but more so for shallower depths. This additionally results in a flatter thickness versus age curve. For given z_0 and F_{tot} the average thickness for given ocean floor age intervals is computed. z_0 and F_{tot} are varied until visually an optimal agreement with the theoretical thickness vs. age curve for half-space cooling has been found.

$$z_L = 2\sqrt{\kappa t} = 10 \text{ km} \sqrt{\text{age}[\text{Ma}]} \quad (8)$$

with $\kappa = 8 \cdot 10^{-7} \text{ m}^2\text{s}^{-1}$ for ages less than approximately 100 Ma. Best-fit values for F_{tot} and z_0 vary between 6.2% and 10%, and 120 and 165 km, respectively (see Table 1). The best fits with the theoretical curve are shown in Figure 3. We regard these good fits as an indication that results are also reasonable on continents. However, we have to caution that this calibration implies that the relation between seismic velocities and temperatures is the same for both continents and oceans. The value for κ was adopted from Sandwell (2001). If a value $10^{-6} \text{ m}^2\text{s}^{-1}$ was used, as is often done, ca. 10% larger thicknesses would result for the theoretical curve. Thus an optimal match would require somewhat larger values for z_0 and/or F_{tot} , leading to somewhat increased lithosphere thickness predictions also elsewhere.

3. Results

3.1. Results based on tomography

Results for lithospheric thickness for this new procedure for different tomography models are shown in Figure 4. Slab related signals have been approximately removed with the procedure as described. Also, a mean thickness model is computed by averaging results for gypsum, s40rts, savani, semum2, and sl2013. This involves mixing estimates based on Voigt average v_S , and on

Table 1: Summary of model parameters. Model: names for tomography model used – gypsum (Simmons et al., 2010), s40rts (Ritsema et al., 2011), savani (Auer et al., 2014), semum2 (French et al., 2013), sl2013 (Schaeffer and Lebedev, 2013). sl2013_dd uses depth-dependent F_{th} and sl2013_nl a non-linear relation between seismic velocity and temperature anomalies (both described in section 2). sl2013_90 and sl2013_78 use values 0.9 and 0.78, respectively, instead of 0.843 in eq. 2 for the base of the lithosphere. F_{tot} and z_0 are parameters of the cutoff function eq. (5), z_{max} is maximum thickness, and $z_{av} \pm z_{std}$ average and standard deviation. For comparison, respective values for the other tomography-based lithosphere thickness models in Figure 1 are also given. Numbers in brackets for z_{max} (323 and 320) indicate that lithosphere thickness found for these models exceeds these values only in very small regions: For semum2 in eastern Tibet (within $92.5^\circ - 95^\circ$ E and $29^\circ - 30^\circ$ N), and around the Persian Gulf (within $47^\circ - 53.5^\circ$ E and $23.5^\circ - 29^\circ$ N), for Pasyanos in Alaska (within $148.5^\circ - 149^\circ$ W and $64^\circ - 64.5^\circ$ N). Also see Table 2 for breakdown by oceanic and continental tectonic regions.

Model	$F_{tot}[\%]$	$z_0[\text{km}]$	$z_{max}[\text{km}]$	$z_{av} \pm z_{std}[\text{km}]$
gypsum	9	130	304	97 ± 55
s40rts	8	140	259	94 ± 50
savani	7	160	273	102 ± 60
semum2	6.6	165	373 (323)	100 ± 64
sl2013	6.2	150	347	96 ± 66
sl2013_dd	6.2	150	400	106 ± 61
sl2013_nl	6.2	150	391	114 ± 57
sl2013_90	6.2	150	400	117 ± 75
sl2013_78	6.2	150	300	76 ± 59
Conrad			270	108 ± 54
Priestley			294	117 ± 36
Bird			254	99 ± 46
Pasyanos			460 (320)	107 ± 66

359 v_{SV} (for models sl2013 and s40rts), but results were not strongly affected by
360 considering radial anisotropy (also see below).

361 Results of all models shown agree that lithosphere is generally thinner in
362 the oceans and thicker on continents (see also Table 2). Within the oceans,

all models also agree on the trend of lithosphere thickness increasing with age. However, there are some differences as to what extent this tendency of thickening continues to the very oldest lithosphere in the western Pacific: Here, model semum2 (French et al., 2013) yields somewhat larger thicknesses than the other models. This is also evident in Figure 3, where semum2 approximately follows the half-space cooling trend including the very oldest ages, in contrast to the other models.

On the continents, all models agree on greater thickness than elsewhere, up to ≈ 250 –300 km, for most cratons (outlines e.g. from Bleeker, 2003; Gubanov and Mooney, 2009) including Laurentia, Baltica, Siberia, Amazonia, West Africa, Congo, Kalahari and Australia. Thinner lithosphere (thickness 100 km or less) is found in many regions near ongoing or recent subduction and/or orogeny, including the western United States, western Europe, and eastern Asia. For much of the North China Craton where removal of a cratonic root has been suggested (e.g., Gao et al., 2002), all models indeed predict thicknesses of less than 100 km, in stark contrast to other cratons. However, all models except for gypsum (Simmons et al., 2010) show thickened lithosphere for at least part of the South China Block. Less than 100 km thin lithosphere is also found in northeastern Africa – thinnest around the Afar region, but extending over large regions thousands of km away from it, but also far from any recent orogeny or subduction (see also McKenzie et al., 2015). In general, models show different levels of detail, with whole-mantle tomography models yielding smoother lithosphere structure than upper mantle models. In particular sl2013 (Schaeffer and Lebedev, 2013) yields more fine-scale structure, also showing some features only a few hundred km wide. A limit of resolution is imposed by the choice of expanding tomography models in spherical harmonics, up to a maximum degree and order of 63.

Without removing slabs (results not shown) the contamination of slab structure is quite obvious for some models, particularly sl2013. However, removing slabs also introduces features (e.g. west of the Himalayas) that may not be real. On the other hand, the RUM model does not have slabs in the Himalaya region,

394 therefore most of our models show thick lithosphere there which may not be
395 real either. In terms of global correlation, though, the removal of slabs hardly
396 matters.

397 Correlations among thicknesses derived from different, global tomography
398 models are shown in Figure 5 based on spherical harmonic expansions up to
399 degree $\ell = 31$ to focus on the commonly resolved wavelengths. Correlations are
400 generally high, as can also be seen from Figure 4. If a fraction 0.9 of the total
401 temperature contrast between surface and adiabatic mantle is used to define
402 the base of the lithosphere, inferred lithosphere thickness somewhat increases
403 (by $\sim 20\%$ on average; Table 1). Conversely, it somewhat decreases (again by
404 $\sim 20\%$ on average) for a fraction 0.78, but it remains very highly correlated in
405 both cases (correlation 0.98 in Figure 5).

406 In the case where the non-linearity of the relation between S -wavespeed and
407 temperature is considered in a simplified fashion, predictions for lithosphere
408 thickness become somewhat larger for both very thin lithosphere and very thick
409 lithosphere, but stay similar around the average thickness. In other words,
410 predicted lithosphere thickness variability somewhat increases for thicker litho-
411 spheres, and decreases for thinner one. But again, results remain very highly
412 correlated at 0.98. Introducing depth-dependent F_{th} modifies results in a simi-
413 lar way as in the non-linear case, but less strongly so. Accordingly, results are
414 very highly correlated at 0.99 with both the original case and the non-linear
415 case.

416 For modification cases sl2013_dd, sl2013_nl, sl2013_90 and sl2013_78 values
417 of F_{tot} and z_0 have not been adjusted to optimize the fit (although that could
418 easily be done), because that would complicate assessing the effects of these
419 modifications.

420 Our procedure relates seismic velocity anomalies (deviations from the mean)
421 to temperature anomalies and accordingly, the degree-zero term (radially sym-
422 metric deviation from reference model) in the tomography models has been
423 removed. We also tested how results are affected, if the degree-zero term is
424 kept, and found that inferred lithosphere thickness changes are ~ 1 km.

Overall, these various modelling assumptions have very little effect on the pattern of lithosphere thickness (correlations are very high) but the thickness values themselves, and their variability (characterized by mean and standard deviation in Table 1) are somewhat more strongly affected.

If simply an isosurface of the tomography models is used to define the base of the lithosphere, results remain highly correlated to those results determined with our procedure, generally ~ 0.85 . So the pattern of lithosphere thickness determined from tomography is really rather robust, independent of tomography model or method used. Our method is still somewhat heuristic but has more of a physical base, compared to some of the methods used previously. We think that using our method is facilitated by a better vertical resolution of more recent tomography models, which now even allows us to infer a compositional layering of the lithosphere discussed in section 3.3. Previously, lack of vertical resolution supposedly prevented imaging the base of the lithosphere directly, such that other, more approximate procedures had to be used (e.g., Bird et al., 2008).

The average lithosphere thickness and amount of variation is somewhat more dependent on which model and procedure are used. Therefore the relative variations of lithospheric thickness are likely to be better determined than the absolute values. For *semum2* and *savani*, where separate models for *SH*, *SV* and Voigt average velocities exist, using identical values for F_{tot} and z_0 , the *SV* models give very similar thickness to the Voigt average, as expected given that $v_{SV}^2 = \frac{1}{3} (2v_{SV}^2 + v_{SH}^2)$ for unity ellipticity. The *SH* model yields somewhat larger thickness (up to few tens of km, for *savani*, less for *semum2*) especially for some of the thicker cratons, as expected for a trade-off with radial anisotropy in the asthenosphere (Gung et al., 2003), but *SH* based patterns are very similar to those for *SV* or Voigt velocities.

Also, results are generally similar to previous lithosphere thickness models based on tomography, with much higher correlations than with lithosphere thickness models based on other methods (Figure 6). Priestley and McKenzie (2006) obtain quite similar thickness on continents, but a less clear dependence on seafloor age in the oceans. The models of Conrad and Lithgow-Bertelloni

(2006) and Bird et al. (2008) can only be compared on continents, where they are based on older tomography models, and hence either show even less detail (in the first case), or a less clear correlation with cratons (in the second). The LITHO1.0 model of Pasyanos et al. (2014) (Figure 1f) shows the greatest similarities to our results, and even more detail structure. In the Tibetan / Himalaya region, the LITHO1.0 has lithosphere less than ≈ 150 km thick, whereas many other tomography-based models show thicker lithosphere there. If lithosphere thickness is computed with our method based on s20rtsb (Ritsema et al., 2004), it becomes visually even more similar to Conrad and Lithgow-Bertelloni (2006), which is based on that tomography model, as expected. For all these and many other models (e.g., Gung et al., 2003; Lekic and Romanowicz, 2011; Jordan and Paulson, 2013), thick lithosphere appears for many cratons.

Mean and standard deviation values for GTR1 (Jordan, 1981) regionalizations are shown in Table 2), for comparison with earlier work. Results are very consistent between models and as expected mirror ocean floor age. Similar to Pasyanos et al. (2014) and Priestley and McKenzie (2013) but different from Bird et al. (2008) and Conrad and Lithgow-Bertelloni (2006), our models tend to show a relatively large thickness for the old lithosphere in the western Pacific, such that the seafloor age vs. lithosphere thickness curve matches the theoretical curve for half-space cooling reasonably well even beyond 100 Ma (Figure 3) (cf., Maggi et al., 2006; Auer et al., 2015).

3.2. Comparison with results based on other methods

In Figure 6 results for the mean, tomography derived thickness model and sl2013 are compared with models derived in a variety of ways. Mean thickness depends on which area is covered. Therefore l_T , which only covers continents, has greater mean thickness than l_S . l_{RF} , which is also mainly determined on continents, however, has similar mean thickness to l_S , although in those regions, where it is determined, it is usually smaller than l_S . Correlations with the mean tomography model are overall somewhat higher than with sl2013, which has been chosen here among the individual models, because it gave the highest

486 correlations in Figure 5.

487 Given the uneven geographic coverage, we compute the linear (Pearson)
488 correlation based on an equal area point sampling of the globe and indicate
489 the fraction of the surface sampled by both models in Figure 6. In general,
490 lower correlations are found for those models not based on tomography. A
491 notable exception is the model for elastic thickness (Audet and Bürgmann,
492 2011), which is highly correlated to tomography-based models, but with elastic
493 thickness being less than the thickness inferred from tomography by a factor $\approx$
494 2. For the Audet and Bürgmann (2011) model, elastic thickness also tends to
495 be comparatively high for most cratonic regions, but not for the North China
496 Craton or the South China block. Elastic thickness is rather small (only about
497 50 km) in the Himalaya / Tibetan region, whereas tomography-based models
498 often feature thicker lithosphere. In Africa, regions of thin elastic lithosphere
499 are mainly near the coasts and in the Afar / Red Sea area. This contrasts
500 to the rather thin lithosphere over wide areas in northeastern Africa found
501 seismologically. In fact, in some areas in Africa, elastic thickness exceeds the
502 thickness determined based on many tomography models.

503 In the map of Artemieva (2006) based on heat flow, thick lithosphere exceed-
504 ing ≈ 200 km is restricted to rather small areas within cratons, leading to rather
505 low correlations of only slightly above 0.5 with thickness based on tomography.
506 Also, correlations with the inverse of heat flow from Davies (2013) is rather
507 low, indicating that variations of radiogenic element concentrations within the
508 lithosphere, and other compositional heterogeneities, contribute significantly, as
509 expected.

510 To better understand these results, regional correlations and ratios are plot-
511 ted in Figure 7. The regional r values are computed based on moving a cap of
512 1000 km radius with equal area point sampling across the globe after filtering
513 each input model first by a Gaussian smoothing operation of 6σ width of 500 km.
514 We also compute best-fit, linear correlation slopes, b , for regions where $r > 0.3$
515 allowing for equal errors in both comparison fields. Any such correlations will
516 be dependent on parameter choices but results can give a rough impression of

517 regional variations in the match between patterns and the typical amplitude
518 ratios.

519 Overall, the mean values of regional correlations based on the moving cap
520 approach of Figure 7 compare between models in a relative sense that is consis-
521 tent with what would be inferred from the global correlations shown in Figure 6.
522 However, the absolute r values themselves are somewhat lower for the regional
523 estimates than for the global correlations, which implies that the correlation
524 between models is generally higher at longer wavelengths.

525 Correlation between tomography and receiver functions is quite variable
526 spatially (Figure 7), and receiver functions tend to give thinner lithosphere,
527 especially in those regions, such as cratons, where thick lithosphere based on
528 tomography is found. This points to the complexity of the interface structure
529 within old continental lithosphere (e.g. Yuan and Romanowicz, 2010; Lekic and
530 Romanowicz, 2011; Fischer et al., 2010; Selway et al., 2015).

531 Similarly, correlation between receiver functions and elastic lithosphere is
532 rather variable. In general, thickness based on receiver functions correlates
533 better to elastic thickness in those regions where it also correlates better with
534 tomography-based thickness, and vice versa. For example, correlation is rela-
535 tively high in the western United States and around the Afar Region, where the
536 lithosphere is presumably thin and therefore less complex.

537 Also, correlation of elastic, receiver-function based, or tomography-based
538 thickness with heat-flow based thickness is quite variable, but with different
539 patterns. Lastly, as expected from the good overall correlation, the correlation
540 between tomography-based and elastic thickness is comparatively high in most
541 regions. One region with rather low correlation, as well as low ratio (b), between
542 tomography-based and elastic thickness, is in northern Africa. Another region
543 with low correlation, but high ratio is the Himalayas and Tibet. In general,
544 the ratio tends to be lower in continental interiors than along margins; elastic
545 thickness determined for continental margins tends to be lower than in the
546 interiors.

547 Audet and Bürgmann (2011) pointed out the correlation of their T_e values

548 with anomalies from seismic tomography, and Figure 8 explores this further.
 549 A good correlation of T_e with all tomography models used here is found – not
 550 only the lithosphere thicknesses based on them, but also the tomography models
 551 themselves, above a depth ≈ 200 km. Correlation tends to be somewhat reduced
 552 above ≈ 100 km. It reaches a maximum at a depth ≈ 100 – 200 km, and drops to
 553 much smaller and even negative values at greater depth, indicating again that
 554 in most regions, the lithosphere does not reach beyond a depth of ≈ 300 km.
 555 Taken at face value, the depth-dependent match of tomographic anomalies with
 556 T_e would imply that the strength that is sensed by T_e (Burov and Diamant,
 557 1995) resides in the lithosphere, not crust. Correlation of elastic thickness with
 558 estimates based on heat flow and receiver functions are much lower, as is also
 559 evident from Figure 6.

560 *3.3. Compositional stratification?*

561 As a further indication that our procedure gives reasonable results, the ap-
 562 parent temperature versus depth averaged for given lithosphere thickness inter-
 563 vals is plotted in Figure 9. These curves were constructed by first converting
 564 profiles of seismic velocity versus depth on a $0.5^\circ \times 0.5^\circ$ grid to apparent tempera-
 565 ture versus depth with eq. (7). These profiles are then averaged for given litho-
 566 sphere thickness ranges but separately for oceanic or continental lithosphere,
 567 according to where the Müller et al. (2008) age grid is defined (Figure 1k). For
 568 example, the red curve for panel “220” is the average profile for all “continen-
 569 tal” grid points, where a lithosphere thickness between 210 and 230 km has been
 570 determined. Individual profiles are weighted according to the area represented
 571 (proportional to cosine of latitude). Since this was computed assuming thermal
 572 scaling between temperature and seismic velocity anomaly locally, but consid-
 573 ering the effect of compositionally different lithosphere on the global average, a
 574 deviation from what is expected can give an indication for compositional differ-
 575 ences. For all except very thin lithospheres it is found that the profiles in their
 576 lower parts agree quite well with the theoretical error function profiles. But
 577 in particular continental profiles show strong deviations in the upper part (cf.

578 Lekic and Romanowicz, 2011).

579 We did the same analysis also for the Voigt velocity of radially anisotropic
580 models semum2 and savani (Auer et al., 2014), to avoid possible trade-off with
581 anisotropy in both oceanic and continental plates (e.g., Gung et al., 2003). Re-
582 sults remain overall similar. For savani, the continental profiles for lithosphere
583 thickness greater than 80 km also show an apparent temperature minimum at
584 similar depths, but not the maximum at even shallower depth. For semum2,
585 profiles for thickness greater than 120 km show again both maximum and mini-
586 mum at similar depths, with continental and oceanic profiles being very similar
587 to each other for thickness between 180 and 120 km. Also, the overshoot to-
588 wards inferred normalized temperatures greater than unity is somewhat smaller
589 for the semum2 model. Comparison with the dashed line corresponding to zero
590 seismic anomaly indicates that the deviation from the theoretical error function
591 profiles, at least in the shallower parts of the continental profiles, is most likely
592 not due to damping.

593 Based on the radial profiles in Figure 9 three different models of a composi-
594 tional lithosphere are created. For model sl2013_c a thickness 150 km is assigned
595 wherever total thickness exceeds 200 km on continents. Between total thickness
596 200 and 75 km, compositional thickness decreases linearly from 150 to 75 km.
597 Below thickness 75 km, and in oceanic regions, values for total thickness are
598 adopted. For models sl2013_c2 and sl2013_c3 individual radial profiles instead
599 of the averaged ones are used at each location. In case c3, the maximum of the
600 apparent temperature profile is taken (if there is a local maximum at depth less
601 than the total lithosphere thickness; if there is none total thickness is adopted;
602 if there are several the deepest one is used). In case c2, the average between the
603 local maximum (as in case c3) and the inflection point is used (if there is one at
604 depth less than the total lithosphere thickness and greater than or equal to the
605 maximum; otherwise the total thickness instead of the inflection point is used).
606 Because in many locations, individual radial profiles are similar to the aver-
607 aged profiles in Figure 9, the different procedures of defining a compositional
608 lithosphere give rather similar and highly correlated results (see also Figure 5).

Based on these compositionally modified models, generally somewhat lower correlations than for the unmodified models (Figure 6) are found. In particular correlations with receiver functions are not improved, but lithosphere thickness values become more similar to the generally smaller thickness determined from receiver functions.

4. Discussion

In the oceanic regions, lithosphere thickness determined with a recently developed procedure versus age matches quite well what is expected from half-space cooling, especially for ages less than about 110 Myr. If the conversion from seismic velocities to temperatures, which is calibrated for the oceans, also holds for the continents, meaningful lithosphere thickness estimates can be derived there. The fact that at least the lower parts of the inferred apparent temperature-versus-depth profiles, averaged for certain lithosphere thicknesses, mostly agrees quite well with theoretical half-space cooling makes this assumption at least plausible.

Deviations of apparent temperature from error function profiles in the upper 100 to 150 km for lithosphere thickness larger than about 100 km in continental regions could be indicative of compositional variations, and their depth range. The shape of this deviation makes it unlikely that this is due to damping. The depth above which deviations occur gets gradually deeper for thicker lithosphere. If lithosphere thickness exceeds 200 km, these deviations mainly occur above 150 km. This is similar to the depths where Yuan and Romanowicz (2010) and Lekic and Romanowicz (2011) propose a compositional layering. One may therefore speculate that this likely compositional effect is linked to the mid-lithospheric discontinuity. Kennett (2015) finds that in Australia a band of P reflectivity commonly occurs close to the mid-lithosphere discontinuity inferred from S wave receiver functions in the cratonic areas.

Thybo (2006) finds a low-velocity zone below a relatively constant depth of 100 km in most continental parts of the world, both in cratonic areas with high

638 average velocity and tectonically active areas with low average velocity. It is
639 hard to assess whether this is related to the above-mentioned deviations of the
640 apparent temperature from error function profiles, which also occurs for most
641 continental regions, because Thybo (2006) considers absolute velocities, whereas
642 we are concerned with velocity variations relative to a mean.

643 Profiles for very thin lithosphere – in particular oceanic ones – often show
644 a temperature maximum, which could be due to higher temperatures in the
645 asthenosphere. If non-linearities in the velocity-temperature relation are con-
646 sidered (Cammarano et al., 2003), this maximum is reduced, but the increase
647 in apparent temperature with decreasing depth in continental lithosphere is not
648 affected by considering non-linearity, hence this appears to be a robust feature
649 showing compositional variation. Also, the upper part of oceanic profiles de-
650 viates from the theoretical error function profiles. However, the shape is less
651 characteristic and the deviation could at least partly be due to damping. A
652 similar clustering analysis of radial profiles has been performed by Lekic and
653 Romanowicz (2011) and Jordan and Paulson (2013). However, our analysis dif-
654 fers in that we (1) group according to the lithosphere thickness of our model
655 and (2) we convert the seismic to apparent temperature profiles.

656 The lithosphere thickness models derived here are similar to other recent
657 tomography-based lithosphere models. The LITHO1.0 model of Pasyanos et al.
658 (2014), shown in their Figure 8, and the model of Priestley and McKenzie (2013)
659 (Figure 1) have thick lithosphere in very similar (cratonic) regions. Also, maxi-
660 mum thickness is rather similar in the LITHO1.0 model or semum2 as analyzed
661 by Lekic and Romanowicz (2011), reaching $\gtrsim 250$ km for some cratons. Gung
662 et al. (2003) find that maximal thickness under cratons is unlikely to exceed
663 250 km – in agreement with the results obtained here, whereas they conclude,
664 based on anisotropy, that deeper structures are a part of the sublithospheric
665 mantle. In accordance with the radial anisotropy trade-off pointed out by Gung
666 et al. (2003), we obtain somewhat thicker lithosphere with our procedure based
667 on *SH* models, whereas *SV* models are very similar to those based on Voigt
668 average (also see Table 2).

Often, thick lithosphere is also inferred for the Tibetan Plateau / Himalaya region (Priestley and McKenzie, 2006), in contrast to thinner lithosphere in other regions of Phanerozoic orogeny. It does not become clear from our work how thick Tibetan lithosphere really is. The traditional view is that this is a region of continental collision, which would explain lithosphere thickening. However, even continental lithosphere may get partially subducted or detach (e.g. Ducea, 2016). In this case, it could be that the lithosphere is in fact not thickened, but due to lack of vertical resolution, the tomography models do not distinguish between the Eurasian lithosphere on top and the subducted Indian lithosphere beneath, and image both as one thick layer (cf. Li et al., 2008). In other regions of subduction, slab signatures have been excluded, but the RUM model of Gudmundsson and Sambridge (1998) which is used for this purpose, does not feature slabs in the Himalaya region, following the traditional view, and we chose not to make any ad hoc adjustments. The fact that elastic lithosphere thickness in the Tibetan / Himalaya region is not higher than in surrounding regions, and that this is the one region where the otherwise good correlation between elastic and tomographic thickness most clearly breaks down (Figure 7) might indicate that indeed the Eurasian lithosphere is not thickened, but underlain by a layer of Indian lithosphere.

Thin lithosphere, similar to orogenic regions, is also found over a rather wide area in northeastern Africa. McKenzie et al. (2015) pointed out that, when reconstructing Pangea, cratons are assembled to one continuous arc of thick lithosphere, surrounding a region of thinner lithosphere that includes northeastern Africa, Arabia and western Europe. Plate reconstructions (Steinberger and Torsvik, 2008; Torsvik et al., 2014) show that northeastern Africa has been overlying the area or margins of the present-day African Large Low Shear Velocity Province in the lowermost mantle for $\sim$ the past 320 Myrs. If this has been a region of upwelling of hot material, this may be a reason for thinner lithosphere. Also presently, material from the Afar plume may be spreading beneath large areas in northeastern Africa and thereby maintaining rather thin lithosphere (e.g. Ebinger and Sleep, 1998; Faccenna et al., 2013).

700 Lithosphere thickness derived from heat flow measurements (Artemieva,
 701 2006) and receiver functions (Li et al., 2007; Rychert et al., 2010) shows quite
 702 a different pattern, with often considerably smaller values. What is inferred to
 703 be the lithosphere-asthenosphere boundary (LAB) from receiver functions is in-
 704 terpreted to be considerably sharper than would be expected from only thermal
 705 effects, and other explanations have been proposed to explain the sharp LAB
 706 (Karato and Jung, 1998; Kawakatsu et al., 2009; Hirschmann, 2010; Karato,
 707 2012; Schmerr, 2012). The issue gets further complicated by the frequent pres-
 708 ence of a MLD: What is interpreted as the LAB by receiver function studies may
 709 be an MLD. It has been suggested that the lithosphere is chemically distinct
 710 mainly above the MLD, whereas the region below is a thermal boundary layer
 711 (Yuan and Romanowicz, 2010; Lekic and Romanowicz, 2011).

712 Our thermal lithosphere models based on tomography are well correlated
 713 with the elastic thickness estimates of Audet and Bürgmann (2011). This prob-
 714 ably indicates that the elastic thickness and by inference, mechanical strength,
 715 is also related to the temperature profile. Elastic thicknesses are typically a
 716 factor of about two less than the thickness derived here. This could mean that
 717 the lithosphere, on long timescales, behaves elastically only for temperatures up
 718 to about half the difference between surface and asthenosphere.

719 Our lithosphere thickness estimates are meant to represent a temperature
 720 isosurface and thus define the depth extent where the mantle is rheologically
 721 strong and thus moves coherently as tectonic plates. In a geodynamic con-
 722 text, we regard this as the most appropriate definition, because in this way,
 723 lithosphere thickness for example determines how well plates couple with the
 724 underlying mantle, and to what extent mantle convection can exert a driving
 725 or dragging force. Since temperature increases gradually, strength probably
 726 also decreases gradually and lithosphere thickness therefore probably cannot be
 727 sharply defined, and any temperature isosurface chosen to define lithosphere
 728 thickness is to a certain degree arbitrary.

729 5. Summary

730 We present models of lithosphere thickness based on a number of recent
731 tomography models, and a recently developed procedure. The plausibility of
732 these models is demonstrated, because (1) in oceanic regions, they overall agree
733 with thickness inferred from lithosphere age and (2) the lower part of inferred
734 radial temperature profiles, which were used to construct these models agrees
735 quite well with theoretical profiles for half-space cooling, in particular if profiles
736 are averaged for given lithosphere thickness ranges. However, strong discrepan-
737 cies occur in the upper part of the profiles, in particular for thick continental
738 lithosphere, probably indicating compositional variations mainly in the upper
739 ≈ 150 km. This substantiates earlier results by Lekic and Romanowicz (2011)
740 based on physics-blind, statistical clustering.

741 Models based on tomography are highly correlated among each other, as well
742 as with other tomography-based lithosphere thickness models. However, aver-
743 age thickness is more dependent on model and procedure. Typically, our model
744 yields lithosphere thickness of about 250 km for cratons, and less in other con-
745 tinental regions. Correlation with thickness estimates based on heat flow and
746 receiver functions are lower. In the case of receiver functions, this could be
747 due to different features “seen” by different methods: The thermal gradients
748 inferred here from tomography is quite gradual, in particular for thick litho-
749 sphere, whereas the receiver function method requires sharper discontinuities.
750 Thickness determined here based on tomography is well-correlated with elastic
751 lithosphere thickness, which is typically about a factor two lower.

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Figure 1: Published lithosphere thickness models and some related quantities. a) l_{RF} inferred from the nearest data point of Rychert et al. (2010) up to five arc-degrees distance; b) l_T Thermal thickness from Artemieva (2006); c) Conrad and Lithgow-Bertelloni (2006), based on tomography model s20rtsb (Ritsema et al., 2004) on continents and an older version of the Müller et al. (2008) age grid; d) Priestley and McKenzie (2013), based on their own surface wave tomography model; e) Bird et al. (2008) based on tomography model s20rts (Ritsema and van Heijst, 2000) on continents and an older version of the Müller et al. (2008) age grid; f) l_{LITHO1} from Pasyanos et al. (2014); g) T_e elastic thickness from Audet and Bürgmann (2011); h) Crustal thickness from CRUST 1.0 (Laske et al., 2013); i) Heat flow (Davies, 2013); k) Seafloor ages (Müller et al., 2008). Cratons from Gubanov and Mooney (2009) in brown, other continents dark green.

Figure 2: A: Sketch of reference and actual temperature profile, lithosphere thickness z_L and reference thickness z_0 . B: Corresponding sketch of seismic velocity anomaly and cutoff function.

Table 2: Lithosphere thickness (average and standard deviation in km) determined for the different GTR1 (Jordan, 1981) tectonic regimes. Tomography models as in Table 1.

model	oceanic	young oc.	intermed. oc.	old oc.	continental	orogenic	Phanerozoic	Precambrian
sl2013	73 ± 37	38 ± 21	75 ± 32	104 ± 33	131 ± 82	95 ± 74	174 ± 72	182 ± 61
gypsum	74 ± 32	38 ± 17	76 ± 25	106 ± 20	134 ± 62	101 ± 45	173 ± 58	179 ± 54
s40rts	74 ± 31	42 ± 18	75 ± 25	107 ± 20	125 ± 57	99 ± 50	155 ± 52	162 ± 40
savani	77 ± 32	48 ± 13	76 ± 25	111 ± 28	140 ± 71	110 ± 67	175 ± 59	187 ± 48
semum2	75 ± 39	35 ± 17	75 ± 30	117 ± 33	140 ± 74	106 ± 64	181 ± 66	188 ± 56
mean	75 ± 31	40 ± 13	75 ± 24	109 ± 22	134 ± 64	102 ± 54	171 ± 57	179 ± 47

Figure 3: Violet line: Lithosphere thickness $z_L[\text{km}] = 10\sqrt{\text{age}[\text{Ma}]}$ obtained from half-space cooling model. Other lines: Average lithosphere thickness for given sea-floor age determined for tomography models as indicated.

Figure 4: Map views of lithosphere thickness determined with our procedure for different tomography models: gypsum (Simmons et al., 2010), s40rts (Ritsema et al., 2011), savani (Auer et al., 2014), semum2 (French et al., 2013), and sl2013 (Schaeffer and Lebedev, 2013). The mean model is an average of these five models. In all cases, slabs-associated anomalies have been approximately corrected for, as described in the text.

Figure 5: Correlations for lithosphere thickness model determined from tomography (cf. Figure 4) based on spherical harmonic expansions up to degree $\ell = 31$. sl2013_90 and sl2013_78 uses a fraction 0.9 and 0.78, respectively, instead of 0.843 for the base of the lithosphere. sl2013_dd uses a depth-dependent F_{th} and sl2013_nl accounts for non-linear relation between seismic velocity and temperature anomalies (both described in section 2). sl2013_c, sl2013_c2, and sl2013_c3 are three models for a chemically layered lithosphere, as described in the text. Numbers on diagonal give average correlation for each model.

Figure 6: Cross-correlations between thickness models. Lower left of matrix shows global, upper right continent-only correlation, r , respectively, with symbol size scaled with the fraction of the surface covered. Diagonal shows mean thickness values, $\langle z \rangle$. Models: l_{RF} : based on receiver functions (Rychert et al., 2010), l_c : crustal thickness from CRUST 1.0 (Laske et al., 2013), l_T : thermal lithospheric thickness from Artemieva (2006), l_{Bird} : lithospheric thickness from Bird et al. (2008), l_{LITHO1} : lithospheric thickness from Pasyanos et al. (2014), T_e : elastic thickness from Audet and Bürgmann (2011), l_S : tomographically determined thickness (our method), mean model and sl2013.

Figure 7: Map views of smoothed lithospheric thickness maps along diagonal (compare Figure 1): Elastic thickness, T_e (Audet and Bürgmann, 2011), thermal lithosphere, l_T (Artemieva, 2006), receiver functions, l_{RF} (Rychert et al., 2010), and the mean, tomographically determined thickness model, l_S . A $6\sigma = 500$ km width, Gaussian smoothing filter was applied. Upper, right part of the plot matrix shows the regional correlations, r , computed from moving a 1000 km radius cap across the domain, and their global mean, $\langle r \rangle$. Lower, left part shows the best-fit linear ratios, b , plotted as $\log_{10}(b)$ for all regions where $b \geq 0.3$, with geometric mean given as $\langle b \rangle_g$.

Figure 8: Correlations with elastic thickness, T_e , from Audet and Bürgmann (2011). Depth-dependent curves are correlations with tomography models' velocity anomalies as a function of depth, vertical lines with lithosphere thickness determined from these tomography models. On the top x -axis, $r(1/q)$ denotes the correlation with the inverse of heat flow from Davies (2013), $r(l_c)$ crustal thickness from CRUST 1.0 (Laske et al., 2013), $r(l_T)$ lithosphere thickness from Artemieva (2006) and $r(L)$ lithospheric thickness from Pasyanos et al. (2014). (For other cross-correlations, see Figure 6).

Figure 9: Profiles of averaged and normalized apparent temperature $\overline{T}(z) - T_s)(T_m - T_s)$, converted from tomography using eq. (7) for given lithosphere thickness intervals, and separately for continents (red) and oceans (blue), for sl2013 (Schaeffer and Lebedev, 2013) tomography. Large numbers indicate values on which thickness intervals are centered. Black lines are error function profiles for this thickness. Black dashed line is the curve that would be inferred for zero anomaly. Small numbers indicate the percentage of total Earth surface area represented by the oceanic/continental curve. Only curves representing more than 0.1% of surface area are plotted.