Global anisotropy and the thickness of continents

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Since the concept of "tectosphere" was first proposed, there have been vigorous debates about the depth extent of continental roots[1,2]. The analysis of heat flow[3], mantle xenoliths[4], gravity and glacial rebound data[5] indicate that the coherent, conductive part of continental roots is not much thicker than 200-250 km. Some global seismic tomographic models agree with this estimate but others indicate much thicker zone of fast velocities under continental shields[6-9], reaching at least 400km in depth. Here we show that the disagreement can be reconciled when taking into account anisotropy. Significant radial anisotropy with Vsh>Vsv is present under most cratons in the depth range 250-400 km, similar to that reported earlier[9,10] at shallower depths (80-250km) under ocean basins. We propose that in both cases, this anisotropy is related to shear in the asthenospheric channel, located at different depths under continents and oceans. The seismically defined tectosphere is then at most 200-250 km thick under old continents. The Lehmann discontinuity, observed mostly under continents around 200-240 km, and the Gutenberg discontinuity, observed under oceans at shallower depths (~ 60-80km), may both be associated with the bottom of the lithosphere, marking a transition to flow-induced asthenospheric anisotropy.

The maximum thickness of the lithosphere, defined as a region of distinctly faster than average seismic velocities (1.5-2%) in global S velocity tomographic models, ranges from 200-400 km, depending on the model[6-9]. This is manifested by a drop in correlation between some models from ~0.80 at 100km to less than 0.45 at 300 km depth (Figure1a), which casts some doubt on the ability of global tomography to accurately resolve upper mantle structure. However, although global Vs models differ from each other significantly in the depth range 200-400km under the main continental shields, these differences are consistent when they are classified into three categories, depending on the type of data used to derive them: 'SV' (mostly vertical or longitudinal component data, dominated by Rayleigh waves in the upper mantle),'SH'(mostly transverse component data, dominated by Love waves), and 'hybrid' (3 component data). 'SH' and 'hybrid' models are better correlated with each other than with 'SV' models. This difference is accentuated when the correlation is computed only across continental areas (Figure 1b). Also, 'SH' (and 'hybrid') models exhibit continental roots that exceed those of 'SV' models by 100 km or more, as illustrated in Figure 2 (see also Figure 1sup).

On the other hand, global tomographic studies that account for seismic anisotropy, either by inverting separately for Vsv and Vsh[9], or in the framework of more general anisotropic theory[10] , have documented significant lateral variations in the anisotropic parameter $\xi=(Vsh/Vsv)^2$ on the global scale. Until now, attention has mostly focused on the strong positive $\delta\ln\xi$ ($\delta\ln Vsh > \delta\ln Vsv$) observed in the central part of the Pacific Ocean in the depth range 80-200 km. The presence of this anisotropy has been related to shear flow in the asthenosphere, with a significant horizontal component. Deeper anisotropy was suggested, but not well resolved in these studies, either because the dataset was limited to fundamental mode surface waves[10], or because of the use of inaccurate depth sensitivity kernels[9]. In particular, it is important to verify that any differences in Vsv and Vsh observed below 200km depth are not an artifact of simplified theoretical assumptions, which ignore the influence of radial anisotropy on depth sensitivity kernels (see Figure 2sup for a comparison of isotropic and anisotropic Vs kernels).

We have developed an inversion procedure for transverse isotropy using three component surface and body waveform data, in the framework of normal mode asymptotic coupling theory[11], which in particular, involves the use of 2D broadband anisotropic sensitivity kernels appropriate for higher modes and body waves (see methods section). Figure 3 shows the distributions of $\delta \ln \xi$ in the resulting degree 16 anisotropic model (SAW16AN)(for the corresponding distributions in Vsh,Vsv, see Figure 3sup), at depths of 175 km, 300 km and 400 km. At 175 km depth, the global distribution of $\delta \ln \xi$ confirms features found in previous studies, and is dominated by the striking positive $\delta \ln \xi$ (Vsh>Vsv) anomaly in the central Pacific[9,10] and a similar one in the Indian Ocean. However, at depths greater than 250 km, the character of the distribution changes: positive $\delta \ln \xi$ emerges under the Canadian Shield, Siberian Platform, Baltic Shield, southern Africa, Amazonian and Australian cratons, while the positive $\delta \ln \xi$ fades out under the Pacific and Indian oceans. At 300 km depth, the roots of most cratons are characterized by positive $\delta \ln \xi$, which extend down to about 400 km. These features are emphasized in depth cross sections across major continental shields (Figure 4) , where we compare Vsh and Vsv distributions, consistently showing deeper continental roots in Vsh. The presence of anisotropy at depths >200km, with Vsh>Vsv, is also consistent with some regional studies[12,13]. Interestingly, the East Pacific Rise has a signature with $\delta \ln \xi < 0$ down to 300km, indicative of a significant component of vertical flow. At 400km depth, we also note the negative $\delta \ln \xi$ around the Pacific ring, consistent with quasi-vertical flow in the subduction zone regions in the western Pacific and south America.

There has been a long lasting controversy regarding the interpretation of shear wave splitting observations under continents, with some authors advocating frozen anisotropy in the lithosphere[14], and others, flow induced anisotropy related to present day plate motions[15]. SKS splitting measurements do not have adequate depth resolution, and inferences that have been made on the basis of a lithospheric thickness of 400 km or more under cratons need to be revisited.

Temperatures in the 250-400 km depth range exceed 1000ºC , and are therefore too high to allow sustained frozen anisotropy in a mechanically coherent lithospheric lid on geologically relevant time scales[15]. Therefore we infer that the Vsh>Vsv anisotropy we describe here must be related to present day flow-induced shear, with a significant horizontal component. Such an interpretation is also compatible with results from shear wave splitting, which document the presence of anisotropy below cratons indicating simple-shear deformation parallel to present day plate motion, at least in North America[16,17] and Australia[13] : some recent studies indicate that there may be two zones of SKS anisotropy under continental shields, one shallower, reflecting past geological events, and one deeper, related to present day flow[16,18].

We note the similarity of the character of Vsh>Vsv anisotropy, in the depth range 200-400km under cratons, and 80-200km under ocean basins, and we suggest that both are related to shear in the asthenosphere, the difference in depth simply reflecting the varying depth of the asthenospheric channel. Although our inference is indirect, it reconciles tomographic studies with other geophysical observations of lithospheric thickness based on heat flow[3], xenoliths[4] and post-glacial rebound data[5]. It is also in agreement with lateral variations in attenuation on the global scale[19].

Another issue greatly debated in the literature is the nature of the Lehmann discontinuity (L), and in particular the puzzling observation that it is not a consistent global feature[20], but is observed primarily in stable continental areas and not under oceans[21,22]. Leven et al.[23] first proposed that L might be an anisotropic discontinuity, and more recent studies have suggested that L is a rheological boundary marking a transition from anisotropic to isotropic structure[24-25]. Since the Vsh>Vsv anisotropy under continental cratons is found deeper than 200 km, we propose that L actually marks the top of the asthenospheric layer, a transition from weak anisotropic lowermost continental lithosphere to anisotropic asthenosphere, in agreement with the inference of Leven et al[23]. Under oceans, the lithosphere is much thinner, and the lithosphere/asthenosphere boundary occurs at much shallower depths. There is no consistently observed discontinuity around 200-250 km depth[20]. On the other hand, a shallower discontinuity, the Gutenberg discontinuity (G), is often reported under oceans and appears as a negative impedance reflector in studies of precursors to multiple ScS[22]. The difference in depth of the observed $\delta\ln\xi>0$ anisotropy between continents and oceans is consistent with an interpretation of L and G as both marking the bottom of the mechanically coherent lithosphere, in areas where it is quasi-horizontal (Figure 5).

In this study, we only consider radial anisotropy, which in particular does not account for intermediate orientation of the fast axis of anisotropy[10]. We can only infer that regions with significant $\delta\ln\xi>0$ are regions where anisotropy has a significant horizontal component, and expresses the alignment of olivine crystals in predominantly horizontal flow[26]. In regions of transition between cratons and younger continental provinces, or between ocean and continent, the asthenospheric flow would follow the inclined shape of the bottom of the lithosphere and be less clearly detected with our approach.

In conclusion, the inspection of radial anisotropy in the depth range 200-400 km allows us to infer that continental roots do not extend much beyond 250km depth, in agreement with other geophysical observations. The part of the mantle under old continents that translates coherently with plate motions need not be thicker than 200-250km. Tomographic models reveal the varying depth of the top of the anisotropic asthenospheric channel, marked by a detectable seismic discontinuity called L under continents (about 200-250km depth), and G under oceans (about 60-80km depth). Finally, seemingly incompatible tomographic models obtained by different researchers can thus also be reconciled: the relatively poor correlation between different models in the depth range 250-400 km is not due to a lack of resolution of the tomographic approach, but rather to the different sensitivity to anisotropy of different types of data.

'Methods'.

Broadband sensitivity kernels

In this study, we invert three component long period seismograms in the time domain (down to periods of 60 seconds for surface waves, 32 seconds for body waves) in the framework of non-linear asymptotic coupling theory (NACT[11]), a normal-mode perturbation-based approach which takes into account the concentrated sensitivity of body-waves to structure along the ray path, in contrast to standard approaches which assume 1D kernels, an approximation which is valid only for fundamental mode surface waves. Our technique involves dividing the seismogram into wavepackets that may contain one or more seismic phases, and applying weighting factors to equalize the contribution of large and small amplitude wavepackets in the least square inversion.

Transverse Isotropy

A transversely isotropic medium with vertical axis of symmetry is described by density ρ and 5 elastic parameters, usually $A=\rho Vph^2$, $C=\rho Vpv^2$, $L=\rho Vsv^2$, $N=\rho Vsh^2$ and F. We start by considering, equivalently, the 6 parameters Vsh, Vsv, $\eta=F/(A-2L)$, Vp_{iso} (isotropic Vp), $\phi=C/A$ and ρ, with appropriate kernels for weak transverse anisotropy. To reduce the number of parameters in the inversion and keep only those that are best resolved ($Vsh=(N/\rho)^{1/2}$, $Vsv=(L/\rho)^{1/2}$), we assume the following scaling relations, as inferred from laboratory experiments for depths relevant to our study (i.e. less than 500km)[27] :

$\delta \ln Vp_{iso} = 0.5\, \delta \ln Vs_{iso}$, $\delta \ln \eta = -2.5\, \delta \ln \xi$ and $\delta \ln \phi = -1.5\, \delta \ln \xi$, with

$\delta \ln Vs_{iso} = 2/3 \delta \ln Vsv + 1/3\, \delta \ln Vsh$ (under the assumption of weak anisotropy; Vs_{iso} is isotropic Vs) and $\delta \ln \rho = 0.3\, \delta \ln Vs_{iso}$. We have verified that the main features in our results are not affected by the particular values chosen in these relations. Starting from our most recent tomographic models, SAW24B16[8] for Vsh and SAW16BV[19] for Vsv, we invert for perturbations in Vsh and Vsv in a spherical harmonics expansion up to degree 16 laterally. Vertical parametrization is in terms of cubic splines. Since our sampling of the lowermost mantle with SV-sensitive body waves is limited, in order to avoid bias from anisotropy in D", we have restricted our inversion to the top 1500km of the mantle, and chosen the body waveforms to include in the dataset accordingly.

We have checked that our results, and in particular the observation of radial anisotropy under continents at depths greater than 200 km is not the result of artefacts due to poor resolution in the inversion for either Vsh or Vsv, by performing synthetic tests. For example, Figure 4sup (supplementary information) shows the results of an experiment in which synthetic transverse component seismograms have been computed for a starting SV model (no roots below 250 km), mimicking the actual distribution of our dataset, and then reinverted for an SH model. No deep continental roots are apparent in the resulting final model.

Assuming lattice preferred orientation (LPO) of anisotropic minerals such as olivine, and as illustrated for example by Montagner[26], a large scale predominantly horizontal flow is characterized by a positive $\delta \ln \xi$ and also significant SKS wave splitting. The direction of the fast axis inferred from the latter is related to the direction of the flow in the horizontal plane. Coupling between Love and Rayleigh waves that may arise in the case of anisotropy with a non-vertical axis of symmetry affects mainly the wave amplitudes. Since we are primarily fitting the phase part of the seismograms, such coupling should have little incidence on our results.

References

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Figure 1. Correlation coefficient as a function of depth between model SAW24B16[8], an 'SH' model, and other global tomographic S velocity models. a) correlation computed over the whole globe; b) correlation computed over continental areas only. Here continents include all areas of elevation greater than -0.5 km. Note that models S20A_SH[9] (an "SH" model) and SB4L18[6] (a "hybrid model") correlate better with SAW24B16 than models S20A_SV[9] and S20RTS[7], which are both "SV" models. The reduced correlation in the depth range 250-400 km between "SH/hybrid" models and "SV" models is strongly accentuated over continents.

Figure 2. Maximum depth for which the velocity anomaly with respect to the reference model PREM[28] is greater than 2%, for different S velocity models. Left: "SH" type models; right: "SV" type models. Bottom: Vsh model SAW24B16[8] compared to Vsv model S20RTS[7]; middle: SH and SV parts of model S20A[9], obtained by inverting T component data and Z,L component data separately; top: SH and SV parts of anisotropic model SAW16AN discussed here. While the roots of continents generally extend to depths greater than 300-350 km in SH models, they do not exceed 200-250km in SV models.

Figure 3. Maps of relative lateral variations in the anisotropic parameter $\delta\ln\xi$ of model SAW16AN at 3 depths in the upper mantle. $\delta\ln\xi>0$ in regions where Vsh>Vsv and $\delta\ln\xi<0$ in regions where Vsv<Vsh. Lateral variations are referred to reference model PREM[28], which is isotropic below 220km depth, but has significant $\delta\ln\xi>0$ at 175km depth. Note how the regions of strong positive $\delta\ln\xi$ shift from the central Pacific to continental areas between 175 and 300 km depth. At depths shallower than 200km, continental shields have mostly $\delta\ln\xi<0$, as noted previously[29]. At 300 km depth, continental shields are no longer prominent in Vsv. At depths greater than 350km, the subduction zones are more prominent in Vsv than in Vsh, resulting in $\delta\ln\xi<0$ around the Pacific, indicative of vertical flow. The East Pacific rise appears as a zone of vertical flow to depths in excess of 300km. Depth resolution is on the order of +/- 50 km.

Figure 4. Depths cross-sections through 3 continents (see location at top) showing the SH (left) and SV(right) components of anisotropic model SAW16AN. The SH sections consistently indicate fast velocities extending to depths in excess of 220 km, whereas the SV sections do not. In section B, the higher velocity associated with the subduction under Kamtchatka is clearly visible in SV but not so much in SH. This anisotropy may contribute to explaining why subduction zones are generally less visible in S tomographic models (mostly of the "hybrid" type, thus more sensitive to SH) than in P models.

Figure 5. Sketch illustrating our interpretation of the observed anisotropy in relation to lithospheric thickness, and its relationship to Lehmann(L) and Gutenberg(G) discontinuities. The Hales discontinuity(H) is also shown. H is generally observed as a positive impedance embedded within the continental lithosphere in the depth range 60-80km[30]. H and G may not be related.

Supplementary material

Figure 1sup. Depth cross-sections across the Canadian Shield, for different SH/hybrid (left) and SV (right) global tomographic models.From bottom to top: left) hybrid models SB4L18[6], S362D1[sup_1] and SH model SAW24B16[8]; right) SV models S20RTS[7], S20A_SV[9] and SAW16BV[19].The models on the left consistently exhibit continental roots that exceed 220 km depth, whereas the models on the right do not.

Figure 2sup. Examples of depth sensitivity kernels for toroidal modes ${}_0T_{40}$ (left) and ${}_1T_{40}$ (right), comparing the case of an isotropic Vs model (grey line), with that of an anisotropic Vs model (PREM[28], black continuous and dotted lines). For the fundamental mode, there is not much difference between isotropic and anisotropic Vsh, whereas for the overtone, the difference is significant in the first 400 km in depth.

Figure 3sup. Maps of relative lateral variations in anisotropic model SAW16AN at 3 depths in the upper mantle. Left: δlnVsh; right: δlnVsv. Lateral variations are referred to reference model PREM[28], which is isotropic below 220km depth.

Figure 4sup. Results of synthetic test in which an input model (middle panels) of the "SV" type is considered (without deep lithospheric roots). Synthetic seismograms for SH component data with the same distribution as our real data collection are computed. The synthetic data thus obtained are then inverted for SH structure, starting from an SH model (SAW24B16[8]) which exhibits deep continental roots (left panels). In the resulting inverted model,no deep continental roots have appeared, consistent with the input model. The rightmost panel shows the correlation as a function of depth of the output model, with, respectively, the input model (SV) and the starting model (SH). The results of this test indicate that the differences in SH and SV models in the depth range 250-400km are not due to an artifact in the inversion process, and in particular to the different depth sensitivity of various SH and SV sensitive phases present in the data.

Reference for supplementary material

1. Gu, Y. J., Dziewonski, A. M., Su, W.-J. & Ekström, G., Models of the mantle shear velocity and discontinuities in the pattern of lateral heterogeneities, J. Geophys. Res., 106, 11169-11199 (2001).

Figure 1

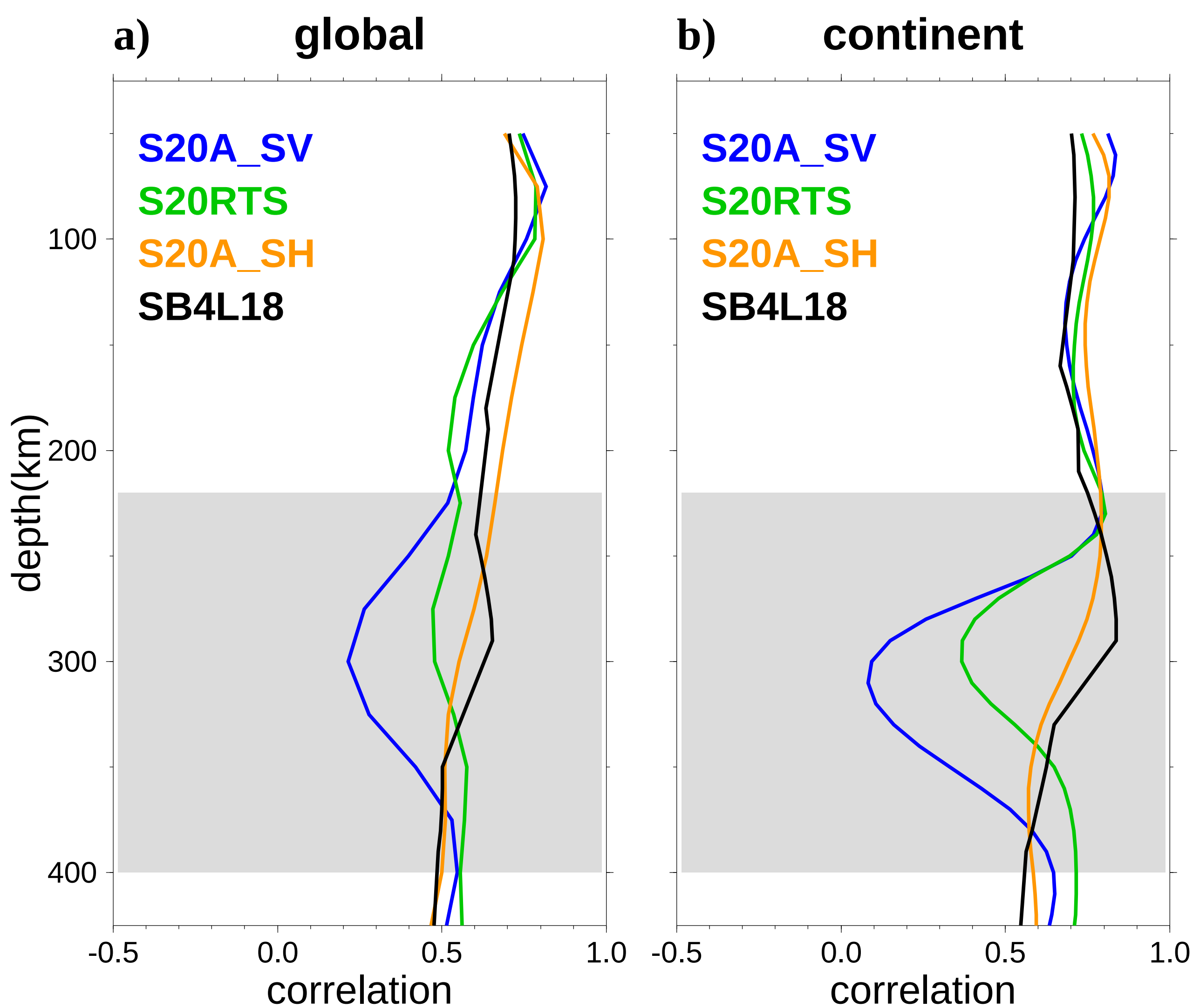

a) global
b) continent
S20A_SV
S20RTS
S20A_SH
SB4L18
S20A_SV
S20RTS
S20A_SH
SB4L18
depth(km)
100
200
300
400
-0.5
0.0
0.5
1.0
correlation
-0.5
0.0
0.5
1.0
correlation

Figure 2

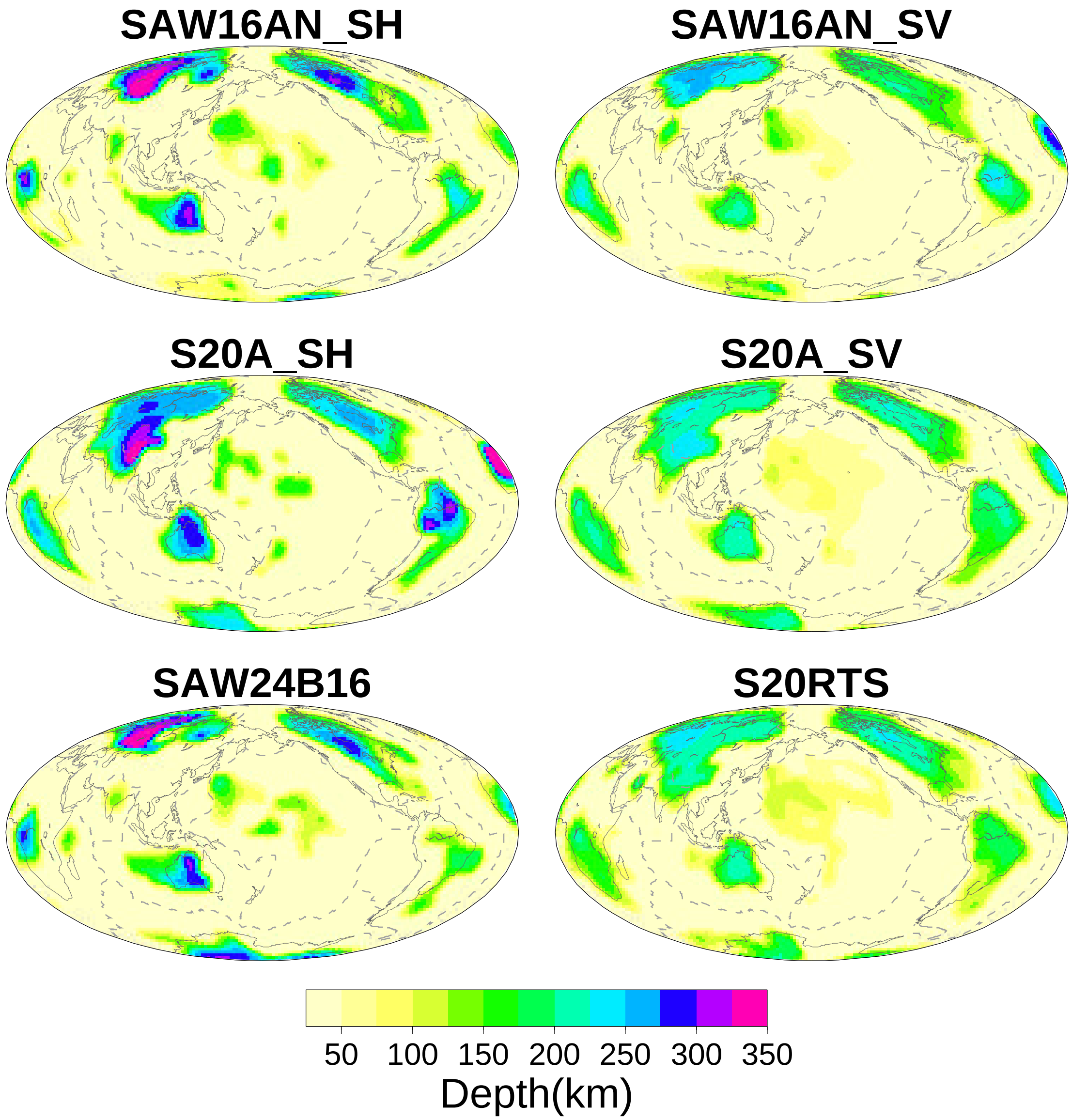

SAW16AN_SH
SAW16AN_SV
S20A_SH
S20A_SV
SAW24B16
S20RTS
50
100
150
200
250
300
350
Depth(km)

Figure 3

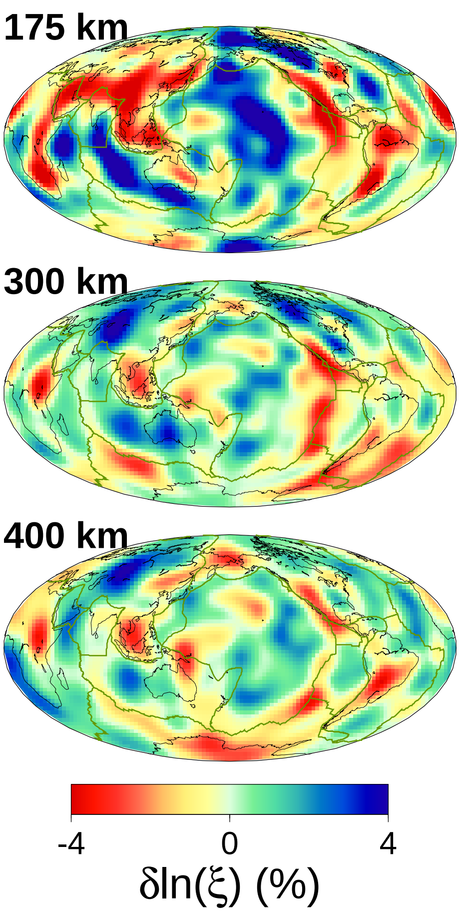


Figure 4

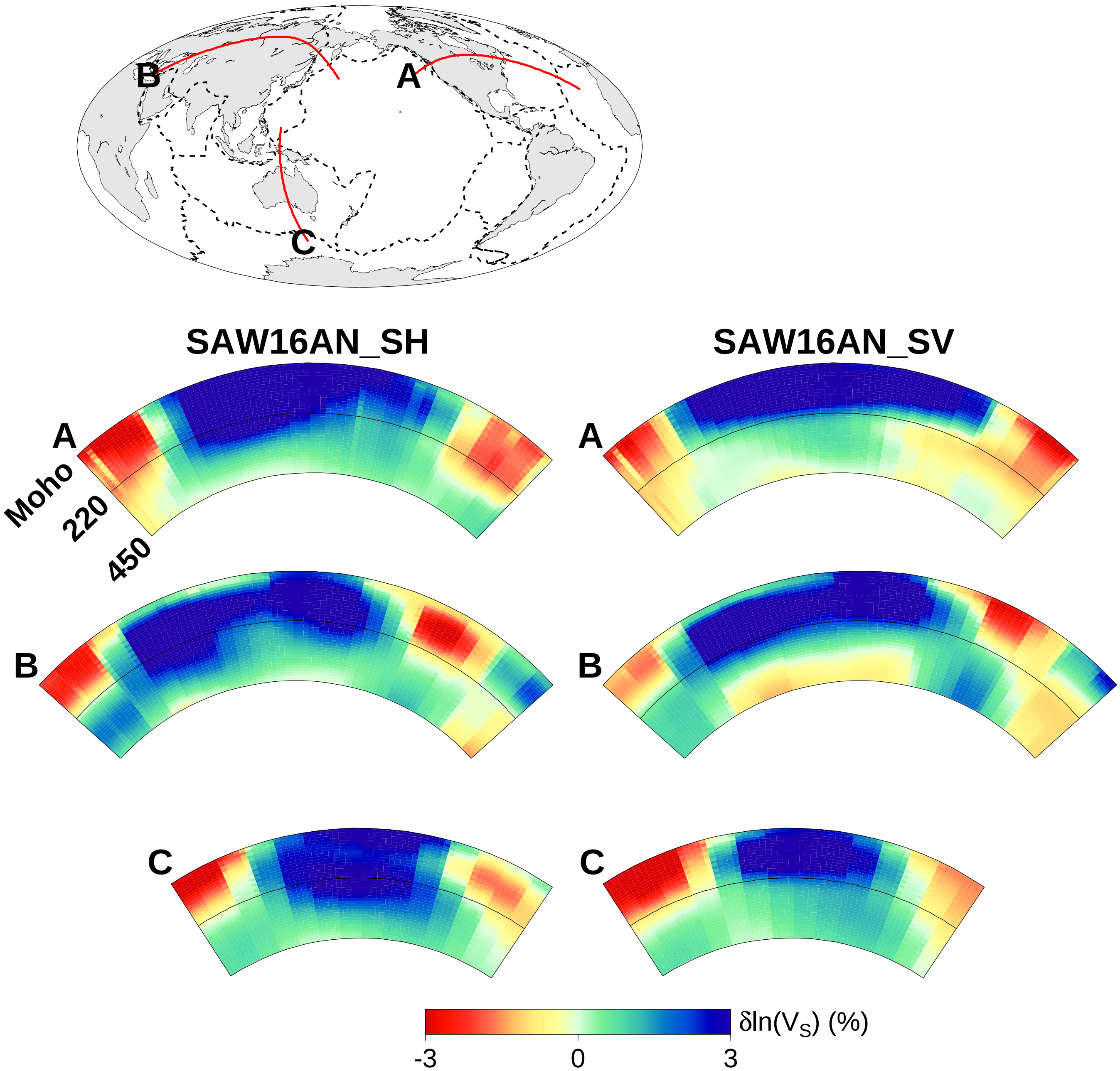


Figure5

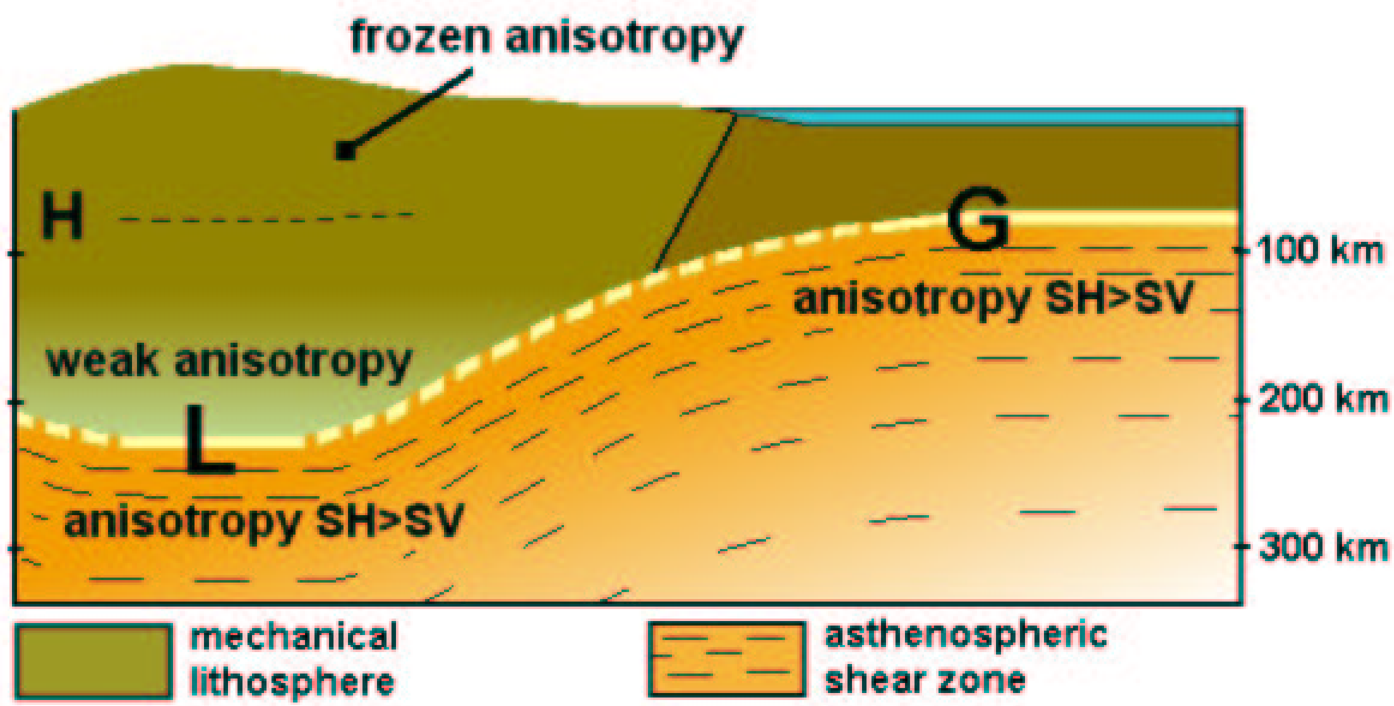
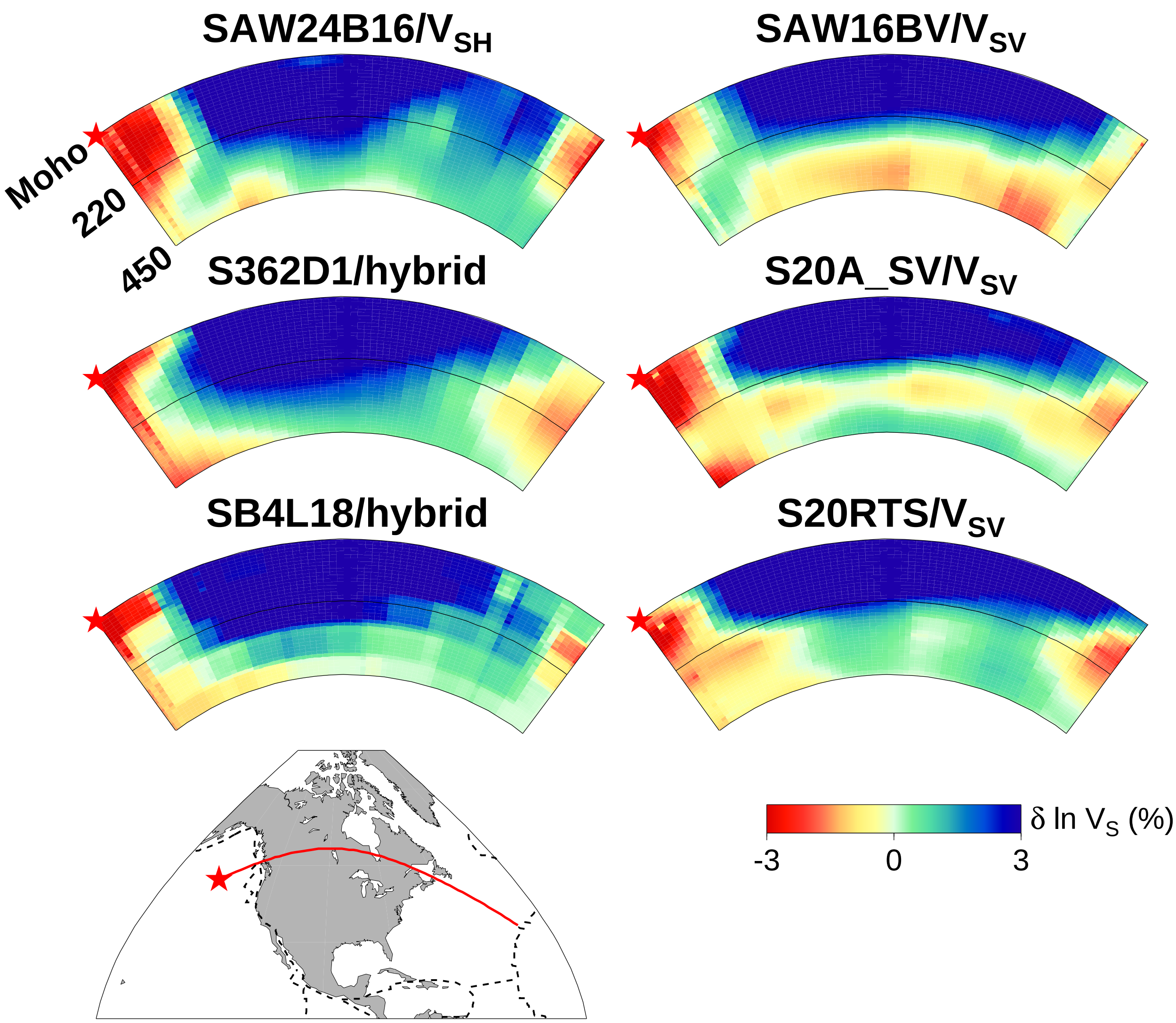
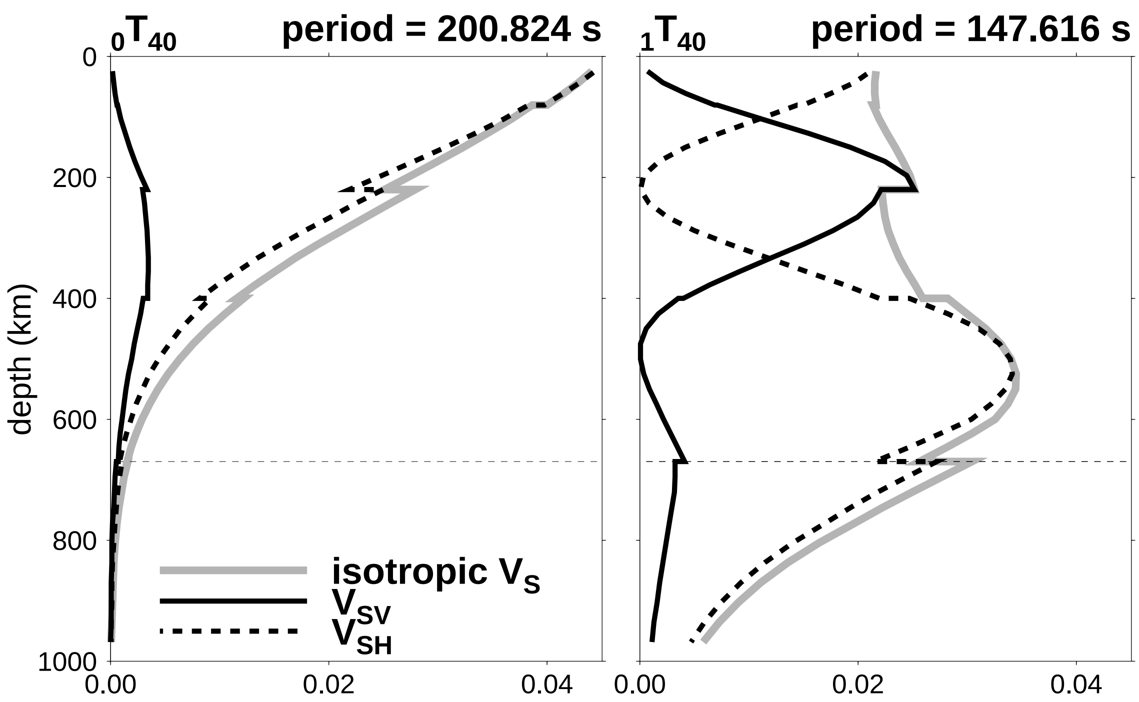

frozen anisotropy
H
G
100 km
anisotropy SH>SV
weak anisotropy
200 km
L
anisotropy SH>SV
300 km
mechanical
lithosphere
asthenospheric
shear zone

Figure1_sup



SAW24B16/V_{SH}
SAW16BV/V_{SV}
Moho
220
450
S362D1/hybrid
S20A_SV/V_{SV}
SB4L18/hybrid
S20RTS/V_{SV}
δ ln V_S (%)
-3
0
3

Figure2_sup



$_0T_{40}$
period = 200.824 s
$_1T_{40}$
period = 147.616 s
depth (km)
0
200
400
600
800
1000
0.00
0.02
0.04
isotropic V_S
V_{SV}
V_{SH}

Figure3_sup

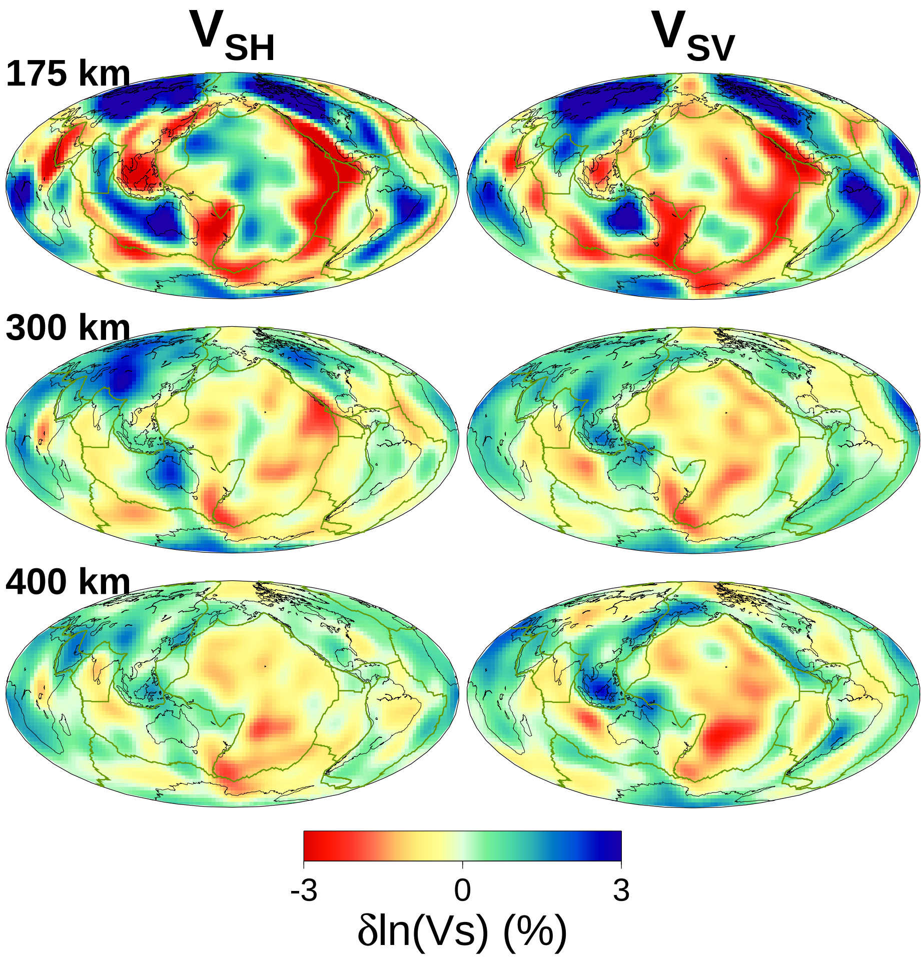
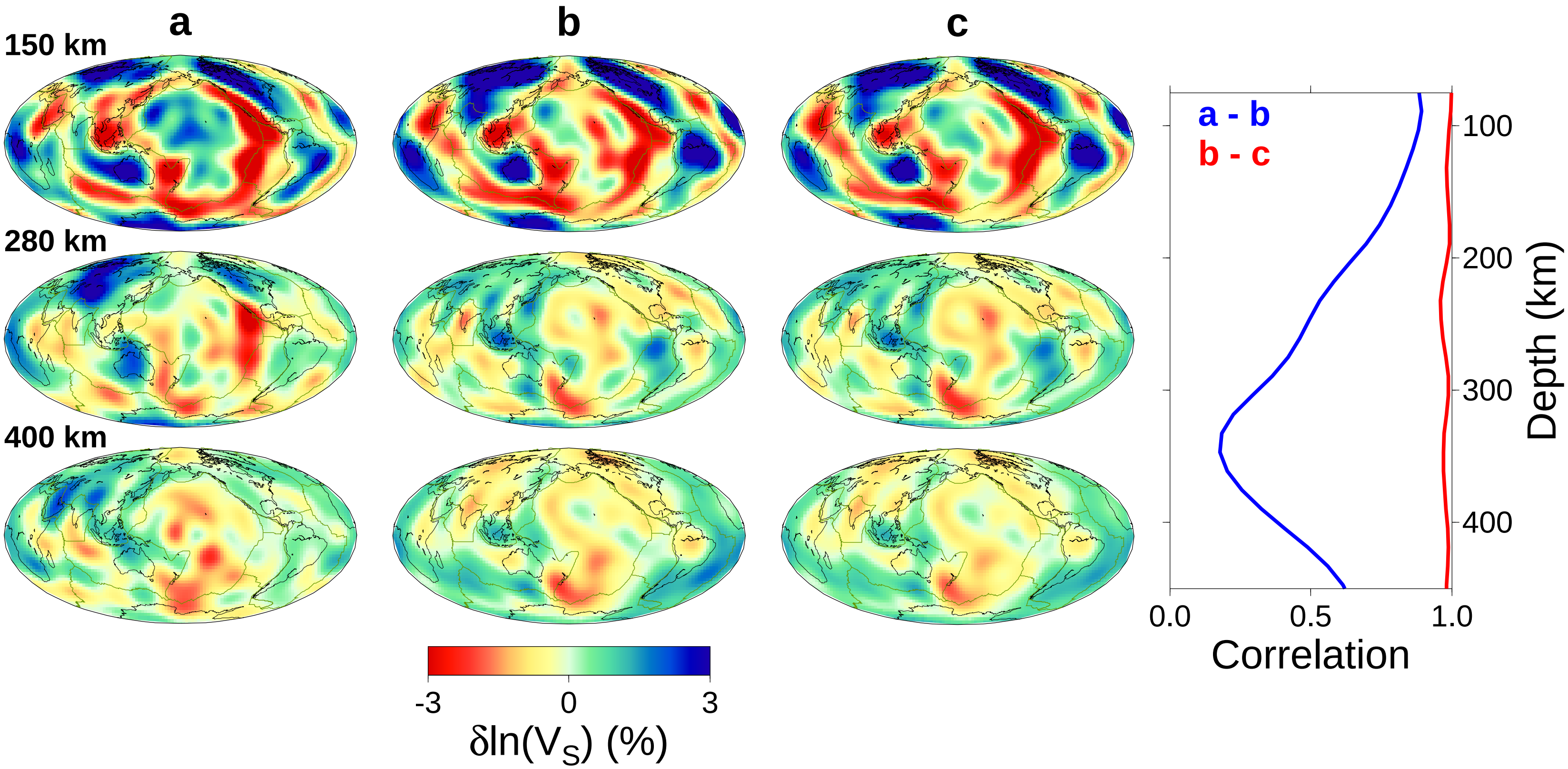


Figure4_sup


a
b
c
150 km
280 km
400 km
-3
0
3
δln(V_S) (%)
a - b
b - c
100
200
300
400
Depth (km)
0.0
0.5
1.0
Correlation