Radial thermo-chemical structure beneath Western and Northern Pacific inferred from seismic waveform inversion

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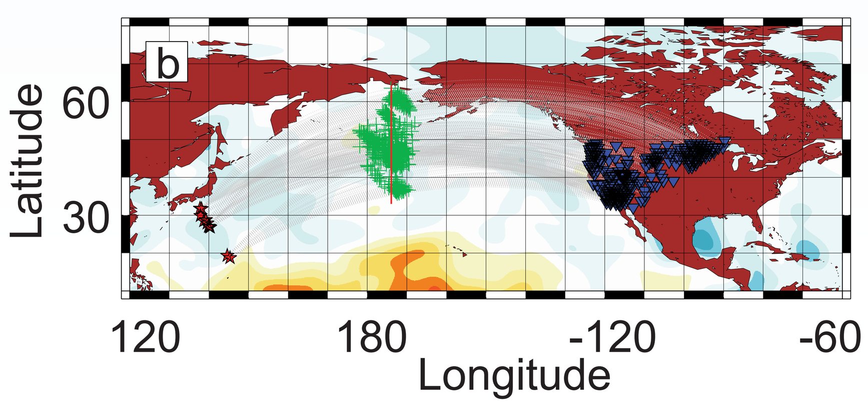
Abstract. The seismic structure of the Earth's deep mantle is dominated by two large low shear-wave velocity provinces (LLSVPs) located beneath Africa and the Pacific. While these structures have been observed by many studies and data sets, their nature, purely thermal or thermo-chemical, is still debated. Shear-wave velocity structure alone is unable to resolve the trade-off between temperature and composition, and discriminating between purely thermal and thermo-chemical hypotheses requires constraints independent from this structure. Seismic shear-wave attenuation, measured by the quality factor Q_S, strongly depends on temperature and may thus bring key information on temperature, resolving in turn the trade-off between temperature and composition. Here, we first invert seismic waveform data jointly for radial models of shear-wave velocity anomalies ($\mathrm{dln}V_S$), and Q_S at two different locations beneath the Pacific, and from a depth of 2000 km down to the core-mantle boundary (CMB). At the Northern Pacific (NP), V_S and Q_S remain close to the PREM values (representing the horizontal average mantle) throughout the investigated depth-range, with $\mathrm{dln}V_S \sim -0.1\%$ and $Q_S \sim 300$ (compared to $Q_{PREM} = 312$). At the Western Pacific location (WP), both V_S and Q_S are substantially lower than PREM. Importantly, $\mathrm{dln}V_S$ and Q_S sharply decrease in the lowermost 500 km, from -0.6 % and 255 at 2500 km, to -2.5% and 215 close to the CMB, respectively. We then show that WP models, sampling the western tip of the Pacific LLSVP and the Caroline plume, cannot be explained by thermal anomalies alone, but require excess in iron of ~ 4.0 % from the CMB up to 2600 km, and ~ 0.8 % at shallower depths. By contrast, NP models may have a purely thermal origin. Our results strongly support the hypothesis that LLSVPs are thermo-chemical structure enriched in iron by a few percent, compared to average mantle composition. We further suggest that the slight enrichment in iron we infer at WP in the depth range 2000-2500 km is related to the entrainment of small amounts of the Pacific LLSVP material by the Caroline plume.

1. Data.

To build models of shear-wave velocity anomalies, $\mathrm{dln}V_S$, and quality factor Q_S, in the lowermost mantle, we inverted S – ScS phases differential waveforms and traveltimes. For the Western Pacific location (WP), we collected broadband waveform data from 1341 seismograms recorded by the Japanese network F-net (77 stations) for 31 deep earthquakes having occurred in the vicinity of Fiji islands. For the Northern Pacific location (NP), we collected broadband waveform data from 601 seismograms recorded by the USArray network (294 stations) for 11 deep earthquakes having occurred in the Japan and Mariana trenches. Figure S1 shows the geometry of sources and seismic stations for both WP and NP.



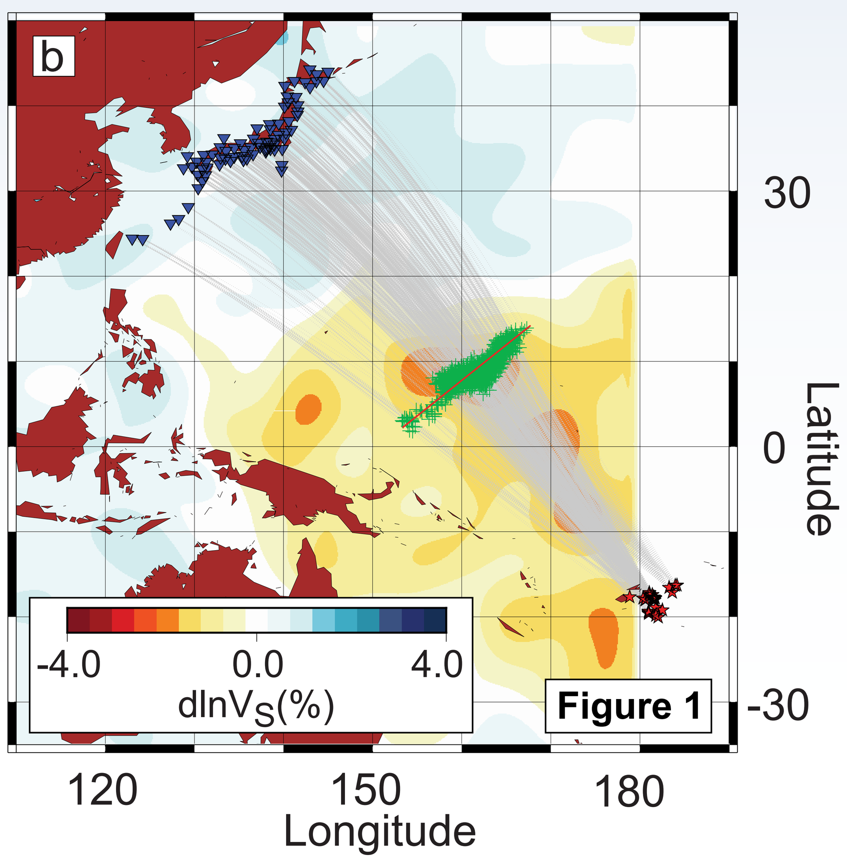


Figure 1

2. Radial models of shear-velocity anomalies and quality factor.

Our models (Figure 2) sample depths ranging from 2000 km down to the core-mantle boundary (CMB), with a radial parameterization of 50 km. Based on resolution tests, uncertainties in $\mathrm{dln}V_S$ and Q_S were estimated to be 0.1% and 15 (Figure 3), respectively. In NP, V_S and Q_S remain slightly lower than their mantle horizontal average, given by PREM, throughout the investigated depth-range, with $\mathrm{dln}V_S \sim -0.1\%$ and $Q_S \sim 300$ (compared to $Q_{PREM} = 312$). At WP, both V_S and Q_S are substantially lower than PREM. Importantly, $\mathrm{dln}V_S$ and Q_S sharply decrease in the lowermost 500 km, from -0.6 % and 255 at 2500 km, to -2.5% and 215 close to the CMB.

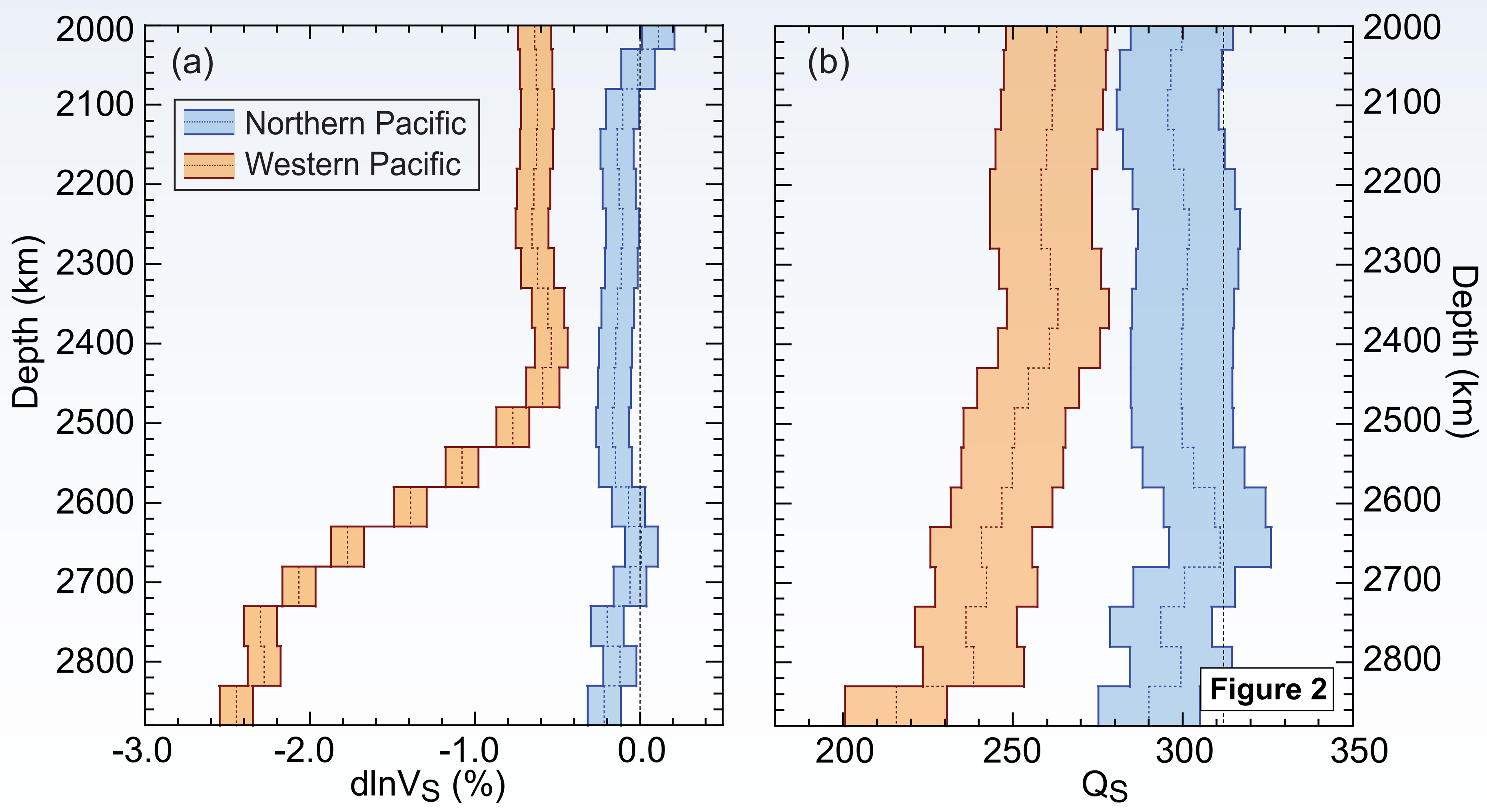


Figure 2

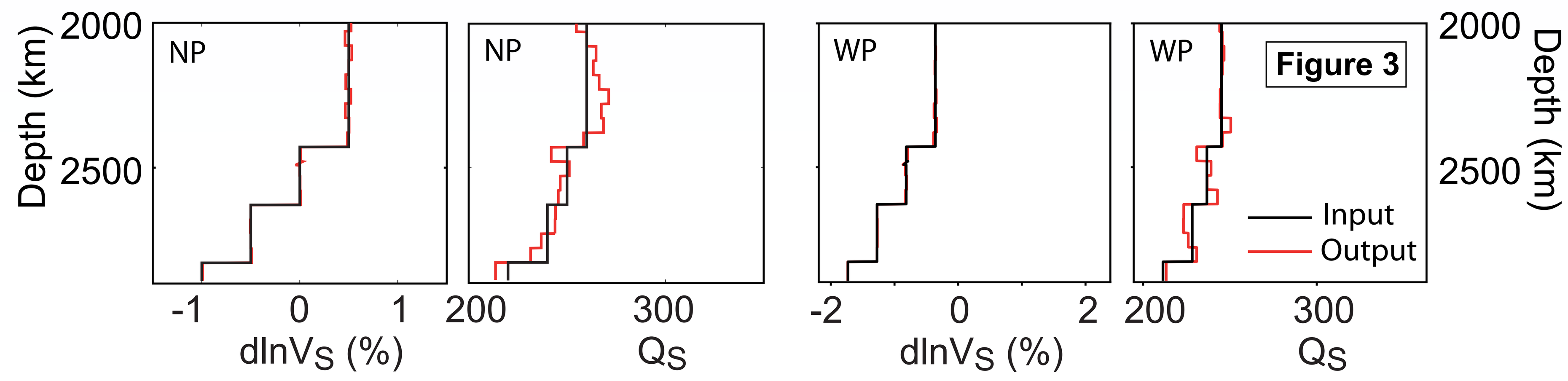


Figure 3

3. Origin of shear-velocity anomalies and attenuation

We calculated temperature anomalies perdicted by models of $\mathrm{dln}V_S$ and Q_S at WP and NP. Temperature anomalies derived from $\mathrm{dln}V_S$ are given by

$$dT_{V_S} = \frac{(\mathrm{dln}V_S - S_{Fe}dx_{Fe} - S_{pPv}dX_{pPv})}{S_T} \qquad (1)$$

where S_T, S_{Fe}, and S_{pPv} are sensitivities of shear-velocity to temperature, iron, and post-perovskite, here taken from Deschamps et al. (2012) and Cobden et al. (2015). Different compositional models (values of dx_{Fe} and dX_{pPv}) in Eq. (1) lead to different estimates of dT_{VS}. Temperature anomalies derived from quality factor are then given by

$$dT_Q = -\frac{RT_{ref}^2}{\alpha H}\frac{\ln\left(\frac{Q_S}{Q_{ref}}\right)}{\left[1+\frac{RT_{ref}}{\alpha H}\ln\left(\frac{Q_S}{Q_{ref}}\right)\right]} \qquad (2)$$

where R is the ideal gas constant, H the activation enthalpy of attenuation, α a factor controlling the frequency-dependence of attenuation, and Q_{ref} the reference quality factor (here, from PREM, $Q_{PREM} = 312$) at temperature T_{ref} (here, the mantle geotherm). In the lowermost mantle, and for seismic wave of periods lower than 200 s, α has been found to be around 0.3 (Lekić et al., 2009).

Computing dT_Q requires the definition of a depth-dependent model for T_{ref} and H, while calculating dT_{VS} needs the prescription of a priori radial models of anomalies in iron and post-perovskite (Figure 4). Close to the CMB, a conservative range for T_{ref} is 3000-4200 K (e.g. Tackley, 2012). At shallower depths, T_{ref} is be estimated by removing from its CMB value a super-adiabatic temperature jump of 500 K in the lowermost 200 km, corresponding to the mantle thermal boundary layer, and an adiabatic gradient of 0.3 K/km. Following Dannberg et al. (2017), we calculated H assuming activation energy and volume in the range 280-380 kJ/mol and 1.1×10^{-6}-1.3×10^{-6} m^3/mol. At the CMB this leads to H in the range 420-570 kJ/mol. We further accounted for uncertainties in measured Q_S and $\mathrm{dln}V_S$, and in seismic sensitivities.

A successful description of the mantle thermo-chemical state at a given location requires that for a set of observed $\mathrm{dln}V_S$ and Q_S, dT_Q and dT_{VS} are equal within their uncertainties.

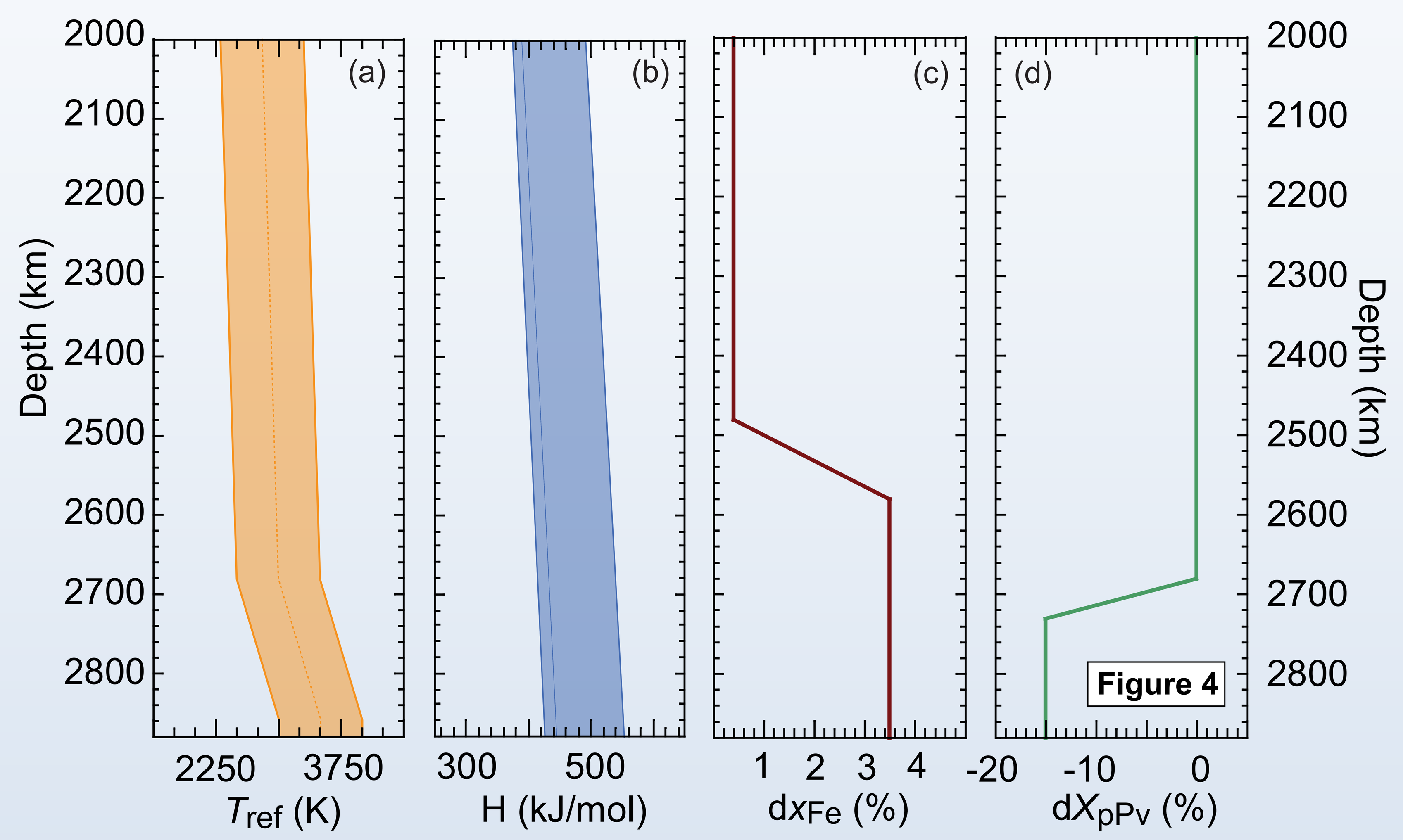


Figure 4

5. Constraints on lowermost mantle thermo-chemical structure beneath the Pacific

We estimated radial models of temperature anomalies at WP and NP independently from $\mathrm{dln}V_S$ (Eq. 1) and Q_S (Eq. 2). At NP (Figure 5a), dT_Q and dT_{VS} obtained for purely thermal $\mathrm{dln}V_S$ ($dx_{Fe} = 0$ and $dX_{pPv} = 0$) are in excellent agreement throughout the depth range we explored. Within error bars, temperature is close to T_{ref}, except in the lowermost 150 km layer, where it is larger by about 50 K. For WP (Figure 5b), dT_Q is around 120-170 K from 2000 down to 2700 km, and increases to 350 ± 200 K at the CMB. Within error bars, dT_{VS} obtained for $dx_{Fe} = 0$ and dx_{pPv} from Figure 4d disagree with dT_Q, in particular from z = 2500 km down to the CMB, where dT_{VS} reaches 800 ± 200 K. By contrast, if accounting for enrichments in iron of 3.5 % in the LLSVP and 0.4 % in the Caroline plume (Figure 4c), dT_{VS} is fully consistent with dT_Q at all depths. Assuming that Q_S is a good proxy for temperature, we calculated a radial model of iron anomalies at WP from observed models of $\mathrm{dln}V_S$ (Fig. 2a) and estimated dT_Q (blue curve in Fig. 4b), and a priori post-perovskite anomalies in Fig. 4d. Throughout a 300 km thick layer above the CMB, explaining $\mathrm{dln}V_S$ requires an iron excess of 3.5-4.5% on average (Fig. 5c), supporting the hypothesis that LLSVPs are enriched in iron oxides by a few percent. Iron excess then regularly decreases upwards, reaching ~ 0.8 % at a depth of 2500 km, possibly due to entrainement of Pacific LLSVP material by the Caroline plume.

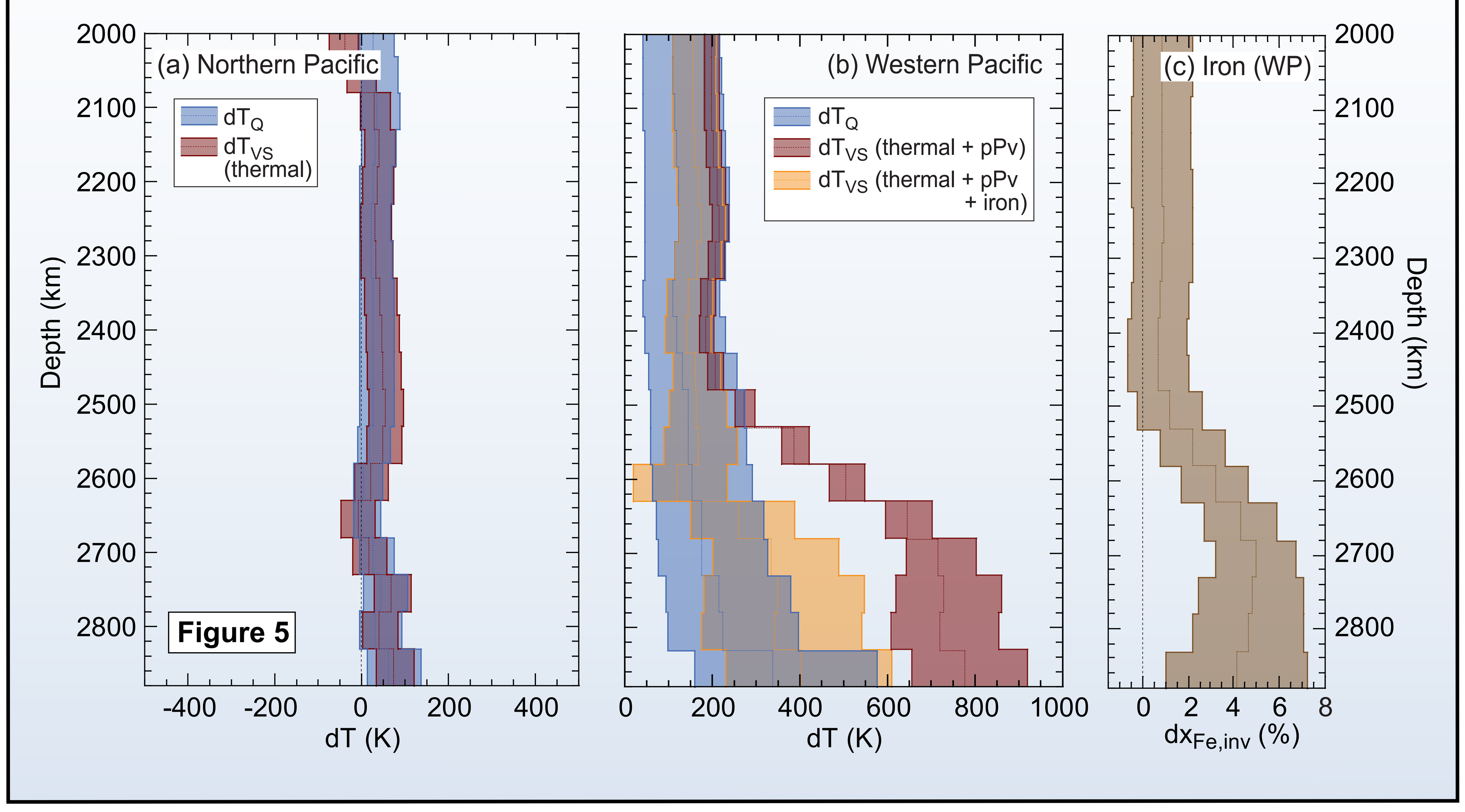


Figure 5

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