Factors contributing to deep slab dip angles in reconstructions of past mantle flow

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Individual sinking slabs present markedly different dip angles between 410 km and 660 km depths, from vertical slabs penetrating the lower mantle to slabs stagnating above the lower mantle. Proposed factors determining these contrasted deep slab dip angles include the magnitude and evolution of trench retreat, mantle viscosity, slab rheology and phase changes. Here we assess the success of paleo-geographically driven global mantle flow models in matching slabs in tomographic models down to 1,000 km depth. We quantify the spatial match between predicted present-day mantle temperature anomalies and vote maps of tomographic models. We investigate the sensitivity of the spatial match to input parameters of the mantle flow model: imposed tectonic reconstruction, model start age, Rayleigh number, viscosity contrast between the upper and lower mantle, and phase changes. We evaluate the visual match between model slabs and tomographic vote maps for three circum-Pacific regions with contrasted deep slab dip angles. The match between predicted model slabs and slabs inferred from tomography can be used to calibrate the Rayleigh number and viscosity contrast between the upper and lower mantle appropriate for our models. The temporal evolution of the models and the global match at present-day suggest that the subduction history could be refined in the global tectonic reconstructions that we considered. For example, subduction to the east of Japan should be offset by approximately 100 km to the west at ˜ 80 Ma to match the anchoring of the plate into the lower mantle suggested by tomography.

Factors contributing to deep slab dip angles in reconstructions of past mantle flow

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Key points

- We compare deep slab dip angles in mantle flow and tomographic models
- Trench retreat, convective vigour and mantle viscosity influence deep slab dip angle
- Our comparison indicates where global tectonic reconstructions could be improved

Abstract

Individual sinking slabs present markedly different dip angles between 410 km and 660 km depths, from vertical slabs penetrating the lower mantle to slabs stagnating above the lower mantle. Proposed factors determining these contrasted deep slab dip angles include the magnitude and evolution of trench retreat, mantle viscosity, slab rheology and phase changes. Here we assess the success of paleo-geographically driven global mantle flow models in matching slabs in tomographic models down to 1,000 km depth. We quantify the spatial match between predicted present-day mantle temperature anomalies and vote maps of tomographic models. We investigate the sensitivity of the spatial match to input parameters of the mantle flow model: imposed tectonic reconstruction, model start age, Rayleigh number, viscosity contrast between the upper and lower mantle, and phase changes. We evaluate the visual match between model slabs and tomographic vote maps for three circum-Pacific regions with contrasted deep slab dip angles. The match between predicted model slabs and slabs inferred from tomography can be used to calibrate the Rayleigh number and viscosity contrast between the upper and lower mantle appropriate for our models. The temporal evolution of the models and the global match at present-day suggest that the subduction history could be refined in the global tectonic reconstructions that we considered. For example, subduction to the east of Japan should be offset by approximately 100 km to the west at ~ 80 Ma to match the anchoring of the plate into the lower mantle suggested by tomography.

Keywords: mantle convection; tectonic reconstructions; tomography; subduction; slab

Plain Language Summary

Oceanic lithosphere is recycled as sinking slabs into Earth's mantle, and the analysis of global earthquake data compiled in tomographic models has revealed that the dip angle of slabs varies between regions. In this manuscript, we analyse the geometry of upper mantle slabs predicted by forward models of past global mantle flow that follow imposed surface tectonic motions. We present some of the first quantifications of the spatial match between the present-day mantle temperature predicted by reconstructions of past global mantle flow and that imaged by global tomographic models. Few studies have quantified this match and clearly exposed it spatially. We quantify the match between the upper mantle slabs predicted by these models and that inferred from a series of tomographic models. We show that the models successfully reproduce the steeply dipping Mariana slab and stagnating Western Pacific slab under Japan and the intermediate geometry of the Farallon and Nazca slab under South America, and we find that trench retreat is the main driver of the geometry of these slabs. Our results suggest that the geometry of slabs can be used to refine global tectonic reconstructions and to calibrate the Rayleigh number and viscosity contrast between upper and lower mantle in global mantle flow models.

Introduction

Global tomographic models have revealed fast velocity anomalies that are interpreted as subducted slabs (oceanic lithosphere that has sunk into Earth's mantle) and that present varying dip angles in the transition zone (between 410 km and 660 km depth) and across the upper-lower mantle boundary (from 660 km depth) (van der Hilst and Mann, 1994; Fukao et al., 2001; Ren et al., 2007; Li et al., 2008; Van der Meer et al., 2018). At these depths, the two most contrasted slab dip angles are slabs penetrating vertically into the lower mantle (such as the Mariana slab) and slabs flattening out in the transition zone (such as the Western Pacific slab) (Van der Hilst et al., 1997; Ren et al., 2007; Běhounková and Čížková, 2008; Li et al., 2008; Goes et al., 2017; Wu et al., 2022). For example, slabs at the Mariana Trench or underneath Peru are steeply dipping through the transition zone sink into the lower mantle, whereas slabs in the Izu-Bonin region or the Western Pacific plate under Japan are more gently dipping through the transition zone and lie flat at the upper-lower mantle boundary (Fukao and Obayashi, 2013; Wu et al., 2022).

Several factors have been proposed to explain the origin of these variations in the dip angles of slabs in the transition zone, which is sometimes referred to as the 'deep slab dip angles' (e.g., Schellart, 2007). These factors include the temporal evolution of the magnitude of trench migration occurring at the surface (van der Hilst and Seno, 1993; Griffiths et al., 1995; Guillou-Frottier et al., 1995; Christensen, 1996; Olbertz et al., 1997; Goes et al., 2017), the viscosity and rheology of the mantle (Hager and Richards, 1989; Peltier, 1996; Čižková and Čadek, 1997; Kido and Čadek, 1997; Čížková et al., 2002; Běhounková and Čížková, 2008; Garel et al., 2014; Mao and Zhong, 2018) and the presence of phase changes (Irifune and Ringwood, 1993; Agrusta et al., 2017; Goes et al., 2017) at around 410 km and 660 km depths. Geodynamic models have also revealed that deep slab dip angles change over time, evolving and developing as part of the convecting mantle (e.g., Agrusta et al., 2017).

Because of their computational cost, investigations of the dynamics of slabs and of their interaction with the mantle transition zone are often carried out in two-dimensions (Čižková and Čadek, 1997; Olbertz et al., 1997; Čížková et al., 2002; Garel et al., 2014; Honda, 2016; Agrusta et al., 2017; Čížková and Bina, 2019; Yang et al., 2019), and the present-day slabs predicted by such dynamically-consistent models are compared to first-order with slabs imaged by tomographic models to the first order. A distinct approach consists of comparing the present-day slab locations predicted by tectonically-driven three-dimensional mantle flow models with that imaged by global seismic tomography models (Becker and Boschi, 2002; Zahirovic et al., 2016; Coltice and Shephard, 2018; Hu et al., 2018; Mao and Zhong, 2018; Peng et al., 2021). Such comparisons are usually visual or consist of global correlations that do not preserve spatial information (Becker and Boschi, 2002), although finer quantitative comparisons are emerging (Flament, 2019; Peng and Liu, 2023).

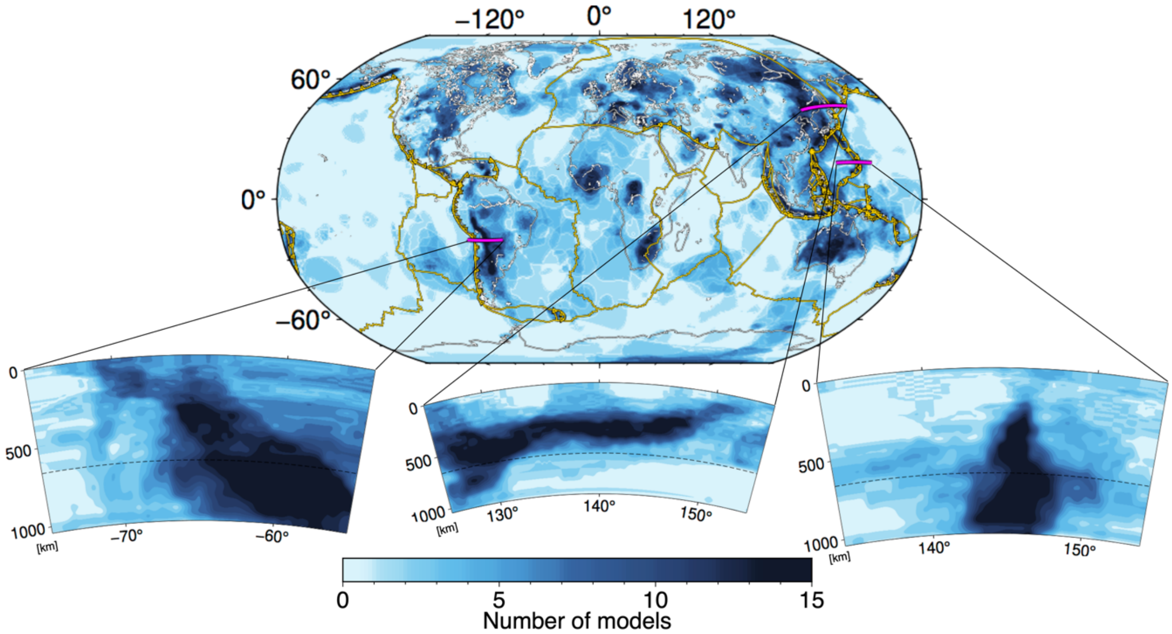


Figure 1. Vote maps for global P-wave tomographic models at 660 km depth and cross-sections down to 1000 km depth for South America, Japan and the Mariana Trench, from left to right. These locations have been selected to show some of the variability in the deep slab dip angles imaged by seismic tomography models. On the maps, golden lines represent plate boundaries (subduction zone polarities are indicated by triangles on the overriding plates), white lines represent coastlines and transects are shown in magenta. On the cross-sections, the dashed line indicated the upper-lower mantle boundary at 660 km depth.

In this study, we quantitively compare the location of present-day slabs predicted by tectonically-driven three-dimensional mantle flow models with that imaged by global seismic tomography models between 400 km and 1000 km depth, a depth range that captures the transition zone and the uppermost lower mantle. Because seismic tomography models are based on different data and methods (e.g., Becker and Boschi, 2002; Romanowicz, 2008; Hosseini et al., 2018), we use an approach that combines them into vote maps that reveal similarities and differences in global seismic velocity models (Shephard et al., 2017). We visually evaluate the deep dip angle of slabs predicted by forward time-dependent global mantle flow models, and for the present-day compare it to vote maps of tomographic models under the Mariana Trench, the Bolivian orocline in South America, and under Japan (Fig. 1). To ascertain whether deep slab dip angle is driven by surface plate motions or by mantle parameters of the flow models, we vary the tectonic reconstruction used as input for mantle flow models, as well as the vigour of mantle convection, the presence of phase changes, and mantle viscosity. Our approach makes it possible to highlight first-order differences between slabs in mantle flow models and in tomographic models, and to recommend modifications to global tectonic reconstructions.

1. Methods

2.1. Paleogeographically constrained mantle flow models

We consider global mantle flow models that take tectonic reconstruction as surface boundary condition to reconstruct the structure of Earth's mantle over time (Bower et al., 2015), and we map model slabs from cold temperature anomalies.

2.1.1 Set-up of forward reconstructions of past mantle convection

We use *CitcomS*, in which the mantle is a shell represented with finite-elements in spherical geometry. We obtain an average resolution of ~50 × 50 × 15 km at the surface, ~40 × 40 ×

100 km in the mid-mantle, and ~28 × 28 × 27 km at the core-mantle boundary (CMB) by using 129 × 129 × 65 × 12 ≈ 13 million elements and refining the mesh vertically towards the surface and the core-mantle boundary. The thermal structure of the lithosphere and of the thermal structure of slabs down to 350 km are built using the half-space cooling model from global maps of the age of the lithosphere (computed from the reconstruction as in Williams et al., 2021) and from the location and polarity of subduction zones obtained from the tectonic reconstructions. The initial condition consists at age a_0 (Table 1) of an adiabat between two thermal boundary layers and of slabs inserted down to z_0 (Table 1) with a dip of 45º down to 425 km and a dip of 90º below 425 km depth. Plate velocities are imposed in one-million-year intervals, and the thermal structure of the lithosphere (down to the base of the lithosphere) and of slabs (down to 350 km depth), computed in one-million-year increments using a diffusive cooling model, are blended in with the dynamic solution at each time step (Bower et al., 2015). This approach makes it possible to obtain one-sided subduction in time-dependent global mantle convection models with computationally affordable resolution and viscosity variations.

2.1.2 Mantle parameters varied across forward reconstructions of past mantle convection

Phase changes. We consider the effect of phase changes at 410 km depth and 660 km depth and assume that both phase changes occur over a 40 km depth range. At 410 km depth, we assume a density change of 3% and a Clapeyron slope equal to 4 MPa K^{-1} (Billen, 2008, and references therein). At 660 km depth, we assume a density change of 7% and a Clapeyron slope equal to -2 MPa K^{-1} (Billen, 2008, and references therein). Case C1 includes phase changes at 410 km and 660 km depth and case C2 includes a phase change at 660 km depth.

Viscosity contrast between the upper and lower mantle. Viscosity varies with depth, composition, temperature and pressure following $\eta = \eta(r)\,\eta_0\ \exp\left\{\frac{[E_\eta+\rho_0 g Z_\eta(R_0-r)]}{[R(T+T_{off})]}-\frac{[E_\eta+Z_\eta(R_0-R_c)]}{[R(T_{\mathrm{CMB}}+T_{off})]}\right\}$, where $\eta(r)$ is a pre-factor that is defined for four layers: above 160 km depth, between 160–310 km depth, between 310–660 km depth and below 660 km depth, η_0 is the reference viscosity, r is the radius, R_C = 3,504 km is the radius of the core, E_η = 275 kJ mol^{-1} is the activation energy, $Z_\eta = 2.1 \times 10^{-6}$ m^3 mol^{-1} is the activation volume, R = 8.31 J mol^{-1} K^{-1} is the universal gas constant, T is the dimensional temperature, T_{off} = 452 K is a temperature offset and T_{CMB} = 3380 K is the temperature at the core-mantle boundary. The viscosity pre-factor, activation energy, activation volume and temperature offset were selected to obtain variations in viscosity over three orders of magnitude (viscosity variations were limited to the range 1.1×10^{20} Pa s - 2.2×10^{23} Pa s) across the range of temperatures and pressures. In all cases except C4, the viscosity pre-factor was ten times greater in the lower mantle than in the upper mantle, because such an increase has been proposed to be required to match the geoid in instantaneous mantle flow models (Hager et al., 1985; Ricard et al., 1993). While this increase is at the lower end of the proposed range (by a factor between 10 and 30; Hager et al., 1985), viscosity also increases with pressure in our models, and the preferred viscosity structure (Fig. 2) is generally consistent with independent models matching the geoid (Steinberger and Calderwood, 2006). Because the viscosity structure of the mantle remains poorly constrained (King, 2016), and because the deep slab dip angles depends on viscosity (Garel et al., 2014), we consider a case without increase at 660 km depth (case C4, Fig. 2).

Rayleigh number. We consider the extended-Boussinesq approximation, which accounts for viscous dissipation, an adiabatic temperature gradient, internal heating and a decrease in the coefficient of thermal expansion by a factor of two over the thickness of the mantle

(Chopelas and Boehler, 1992). Convective vigour is determined by the Rayleigh number $Ra = (\alpha_0 \rho_0 g_0 \Delta T h_M^3)/(\kappa_0 \eta_0)$ with $\alpha_0 = 3 \times 10^{-5}$ K^{-1} the coefficient of thermal expansion, $\rho_0 = 4000$ kg m^{-3} the density, $g_0 = 9.81$ m s^{-2} the gravitational acceleration, $\Delta T = 3100$ K the temperature change across the mantle, $h_M = 2{,}867$ km the thickness of the mantle, $\kappa_0 = 1 \times 10^{-6}$ m^2 s^{-1} the thermal diffusivity and $\eta_0 = 1.1 \times 10^{21}$ Pa s the viscosity, and the subscript "0" indicates reference values. With the values listed above, $Ra = 8.60 \times 10^8$. The Rayleigh number (Ra) is increased in increments of an order of magnitude between 8.60×10^6 and 8.60×10^9 across model cases C5-C8 (Table 1). The dissipation number that controls shear heating is $Di = (\alpha_0 g_0 R_0)/C_{p_0}$; with $R_0 = 6{,}371$ km the radius of Earth and $C_{p_0} = 1200$ J kg^{-1} K^{-1} the heat capacity, $Di = 1.56$.

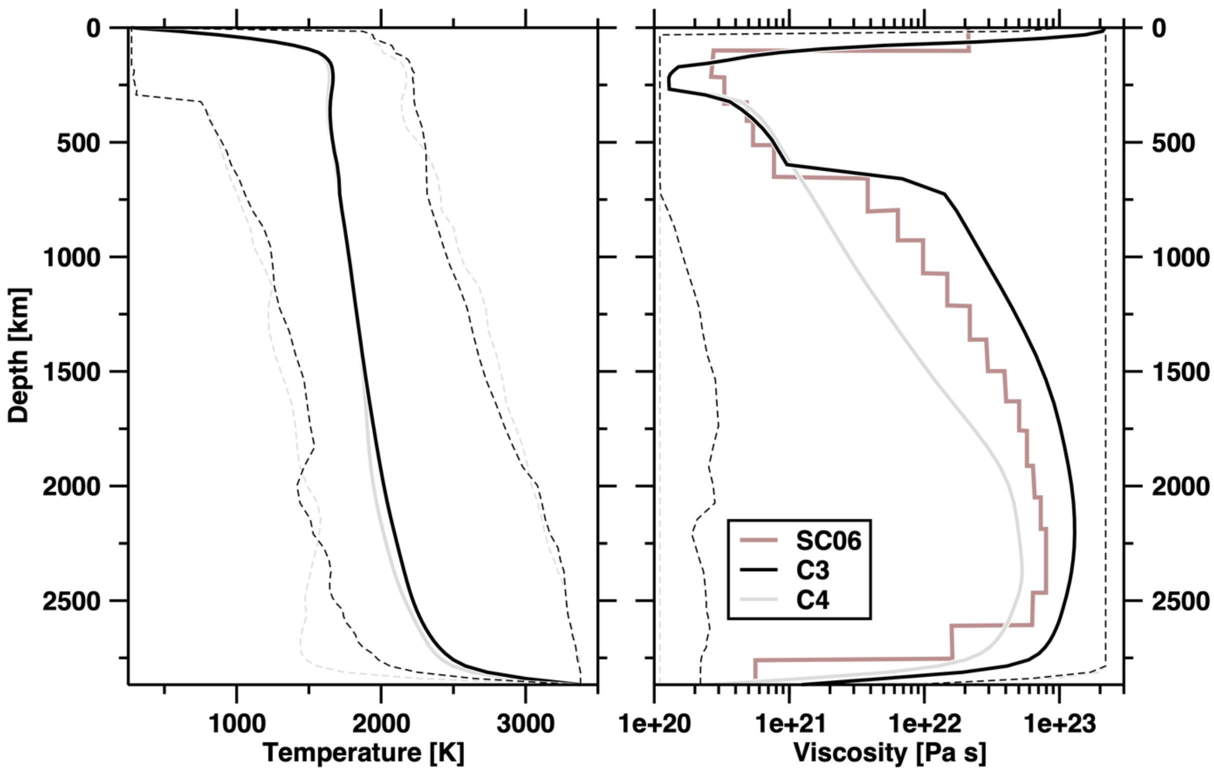


Figure 2. Variations of temperature (left) and viscosity (right) with depth predicted for the present-day for cases C3 (with a viscosity contrast at 660 km depth) and C4 (without viscosity contrast at 660 km depth). Solid lines show the horizontal average and dashed lines show the minimum and maximum. 'SC06' is a viscosity model from Steinberger and Calderwood (2006) calibrated to fit the present-day geoid.

Tectonic reconstructions. We vary the model start age a_0 and the tectonic reconstruction across a series of model cases. We consider the tectonic reconstructions of Müller et al. (2016), hereafter referred to as Mu16, Matthews et al. (2016), hereafter referred to as Ma16, Young et al. (2019), hereafter referred to as Y19, and Merdith et al. (2021), hereafter referred to as Me21. Reconstruction Mu16 was used for case C9 (a_0 = 230 Ma); it extends back to 230 Ma and uses the reference frames of Steinberger and Torsvik (2008) between 200-100 Ma and of Torsvik et al. (2008) for the last 100 Myr. Reconstruction Ma16 was used for case C5-C8, C11 (a_0 = 100 Ma) and C12 (a_0 = 230 Ma) and C11; it is similar to reconstruction Mu16 for the last 230 Ma, although it uses the reference frame of Torsvik et al. (2012); for the period 410-230 Ma, it is based on the reconstruction of Domeier and Torsvik (2014). Reconstruction Y19 was used for case C10 (a_0 = 410 Ma); it is based on Ma16 with modifications to decrease global tectonic speeds and trench migration rates, including changes to relative plate motions (closure of the Rheic Ocean and motion of circum-Paleo-Tethys blocks) and using the reference frame of Torsvik and Voo (2002). Reconstruction M21 was used in case C1-C3 (a_0 = 1000 Ma); it links the reconstruction of Merdith et al. (2017) for the period 1000-500 Ma, to the reconstructions of Domeier (2016) and Domeier (2018) for the period 500-410 Ma and to reconstruction Y19 for the last 410 Myr. Reconstruction M21 includes the correction to the mantle reference frame suggested by Torsvik et al. (2019) for Panthalassa. We modified the original reference frame of reconstruction M21 that is based on paleomagnetic data by removing the wholesale motion of the lithosphere with respect to the mantle, known as net lithospheric rotation, because imposing lithospheric net rotation induces wholesale motion of the mantle (Rudolph and Zhong, 2014) whereas such motions should dynamically arise from lateral viscosity variations (Ricard et al., 1991).

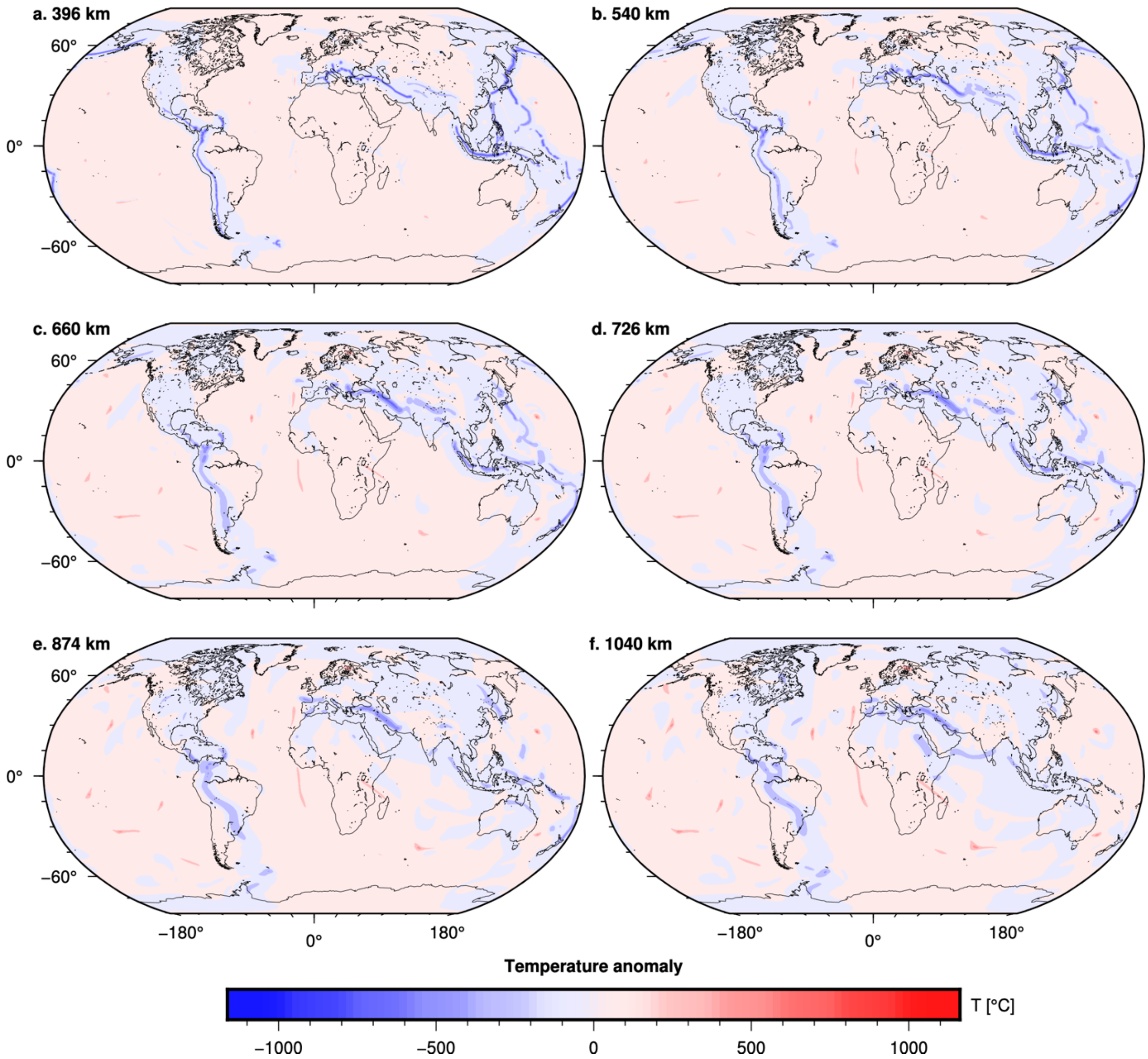


Figure 3. Present-day temperature anomalies defined as deviations from the horizontal average of temperature such as shown in Figure 2, for selected depths and for case C10 (reconstruction Y19, start age 410 Ma). Coastlines are shown in black.

Most of these models have previously been reported in publications: cases C1, C2 and C3 were cases C22, C21 and C20 in Flament et al. (2022), respectively, and cases C5, C6, C7, C8, C9 and C12 were cases C11, C12, C1, C13, C4 and C6 in Flament (2019).

These reconstructions of past mantle flow predict present-day mantle temperature (Fig. 3) from which slabs can be inferred. Overall, the varied parameters make it possible to separately investigate the effect on deep slab dip angle of initial and surface boundary conditions (tectonic reconstruction and start age) and of parameters affecting mantle convection (Rayleigh number, viscosity structure, phase changes).

Case	Reconstruction	Start Age (Ma)	Rayleigh Number	Viscosity structure	Phase change
			Phase change		
C1	M21	1000	$8.60x10^8$	0.02,0.002,0.02,0.2	410, 670
C2	M21	1000	$8.60x10^8$	0.02,0.002,0.02,0.2	670
C3	M21	1000	$8.60x10^8$	0.02,0.002,0.02,0.2	-
			Viscosity contrast		
C4	M21	1000	$8.60x10^8$	0.02,0.002,0.02,0.02	-
			Rayleigh number		
C5	Ma16	230	$8.60x10^6$	0.02,0.02,0.02,0.1	-
C6	Ma16	230	$8.60x10^7$	0.02,0.02,0.02,0.1	-
C7	Ma16	230	$8.60x10^8$	0.02,0.02,0.02,0.1	-
C8	Ma16	230	$8.60x10^9$	0.02,0.02,0.02,0.1	-
			Tectonic reconstruction		
C9	Mu16	230	$8.60x10^8$	0.02,0.02,0.02,0.02	-
C10	Y19	410	$8.60x10^8$	0.02,0.002,0.02,0.2	-
C11	Ma16	100	$8.60x10^8$	0.02,0.002,0.02,0.2	-
C12	Ma16	230	$8.60x10^8$	0.02,0.002,0.02,0.2	-

Table 1. List of paleogeographically constrained mantle flow models grouped by input parameters.

2.2. Slabs imaged by vote maps of seismic tomographic models

Seismic tomography is one of the main techniques to image Earth's mantle. Regions in which P- and/or S-waves travel faster than a reference model such as PREM (Dziewonski and Anderson, 1981) are inferred to be colder than ambient mantle and to represent slab material that has sunk into the mantle. Seismic tomographic models differ in the data and methods used (Becker and Boschi, 2002; Romanowicz, 2008; Hosseini et al., 2018); for example, S-wave models tend to achieve better coverage of the mantle than P-wave models, although at lower resolution (Grand, 2002). A way to jointly analyse distinct tomographic models is to create 'vote maps' that contour and stack seismic velocity anomalies from different tomographic models, either by analysing models over a given depth range using cluster analysis (Lekic et al., 2012), or by analysing models at discrete depths (Shephard et al., 2017; Shephard et al., 2021). Here we follow the latter approach to preserve the location of slabs as a function of depth. In the process, areas in which seismic velocity anomalies are greater than the mean of the positive values are attributed a value of one, whereas other areas are given a value of zero; global maps for selected tomographic models are then added together for a given depth (Shephard et al., 2017). The resulting vote maps depend on the number of selected models, and do not add any features that were not present in the underlying tomographic models. The resulting vote maps reveal where tomographic models agree on the presence of fast seismic anomalies, interpreted as slabs. Greater vote counts indicate features that are common across the selected models, whereas lower vote counts indicate features that are only present in fewer models; however, low vote counts do not indicate that features do not exist. Here we created vote maps (e.g., Fig. 8) from the SubMachine website (Hosseini et al., 2018; Hosseini, 2018), focusing on global tomographic models and ignoring models restricted either regionally or in depth. We selected deviations from the mean for fast velocity anomalies down to 1000 km depth for the following global tomographic models:

- 15 P-wave tomographic models: DETOX-P1, DETOX-P2, DETOX-P3 (Hosseini et al., 2020), GAP-P4 (Obayashi et al., 2013), GyPSuM-P (Simmons et al., 2010), HMSL-P06 (Houser et al., 2008), LLNL_G3Dv3 (Simmons et al., 2012), MITP08 (Li et al., 2008), MITP_USA_2011MAR (Burdick et al., 2012), MITP_USA_2016MAY (Burdick et al., 2017), PRI-P05 (Montelli et al., 2006), SP12RTS-P (Koelemeijer et al., 2016), SPani-P (Tesoniero et al., 2015), UU-P07 (Amaru, 2007), TX2019slab-P (Lu et al., 2019)
- and 18 S-wave tomographic models: GyPSuM-S (Simmons et al., 2010), HMSL-S06 (Houser et al., 2008), PRI-S05 (Montelli et al., 2006), S20RTS (Ritsema et al., 1999),

S362ANI+M (Moulik and Ekström, 2014), S40RTS (Ritsema et al., 2011), Savani (Auer et al., 2014), SAW642ANb (Panning et al., 2010), SEISGLOB1 (Durand et al., 2016), SEISGLOB2 (Durand et al., 2017), SEMUCB-WM1 (French and Romanowicz, 2014), SEMum (Lekić and Romanowicz, 2011), SGLOBE-rani (Chang et al., 2015), SP12RTS-S (Koelemeijer et al., 2016), SPani-S (Tesoniero et al., 2015), TX2011 (Grand, 2002), TX2015 (Lu and Grand, 2016), TX2019slab-S (Lu et al., 2019).

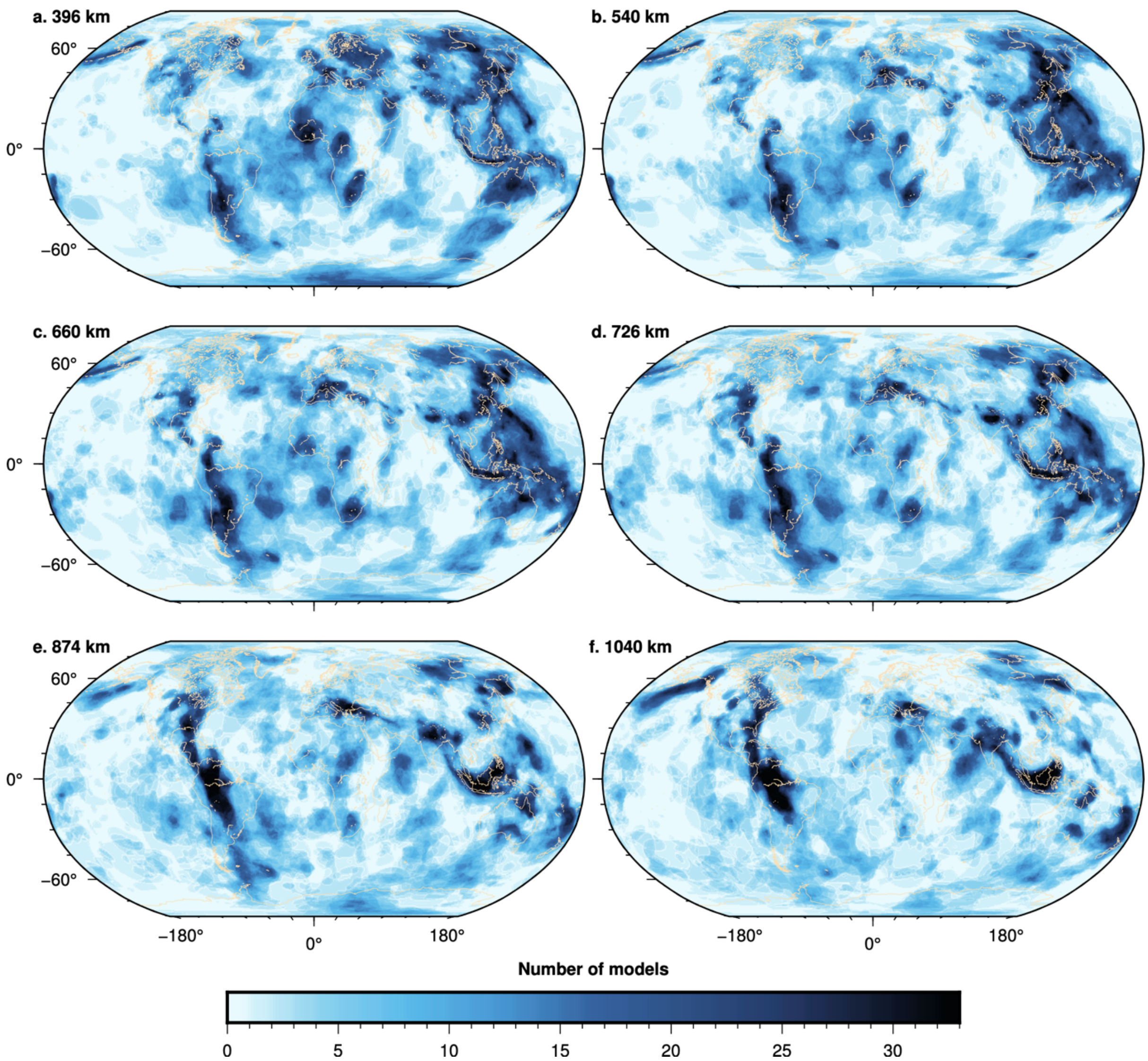


Figure 4. Vote maps for 33 global P- and S-wave tomographic models shown at selected depths. Coastlines are coloured in gold.

2.3 Comparing slabs in mantle flow models and in tomographic models

The considered mantle flow models are not directly based on tomographic models, which makes it possible to compare the temperature structure predicted for the present day to tomographic models. Specifically, we aim to compare the location and deep slab dip angle of predicted cold mantle structures to that of fast seismic anomalies summarised in vote maps from tomographic models. We achieve this comparison by selecting threshold values for predicted temperature anomalies and vote maps of tomographic models. In carrying out this comparison, we keep in mind that tomographic models have been used to regionally refine the global tectonic reconstructions that we use (e.g., Zahirovic et al., 2016). While the initial temperature structure of our forward mantle flow models is derived from tectonic reconstructions rather than from tomographic models, the reconstructions that we use have been informed by tomographic models in some regions for the last ~150-200 Myr, assuming that slabs sink vertically at uniform sinking rates (e.g., Zahirovic et al., 2016).

2.3.1 Selecting thresholds to obtain similar slab cross-sectional areas

To visually and quantitatively compare the spatial match between present-day slabs predicted by mantle flow models and imaged by tomographic models, it is important to ensure that the area of slabs is similar in both types of models. We investigate the area covered by slabs in map view at a given depth for a given threshold of temperature anomalies and vote map, following Flament (2019). We first consider mantle 2% colder than ambient and 7 votes out of 15 P-wave tomographic models (as in Flament, 2019), 11 votes out of 18 S-wave tomographic models and 17 votes out of 33 P- and S-wave tomographic models. These thresholds lead to slabs covering 5-10% of the surface between 400 km and 1000 km depth (Fig. 5a) in tomographic models, and while some flow models fall within that range, the fractional area reaches up to 22% of the surface in case C3. Considering mantle 5% colder than ambient, 13 votes out of 15 P-wave tomographic models, 14 votes out of 18 S-wave tomographic models and 23 votes out of 33 P- and S-wave tomographic models decreases the slab area to between ~1.5% and 6% and results in a better match between mantle flow and tomographic models (Fig. 5b). We therefore use these latter thresholds in the following.

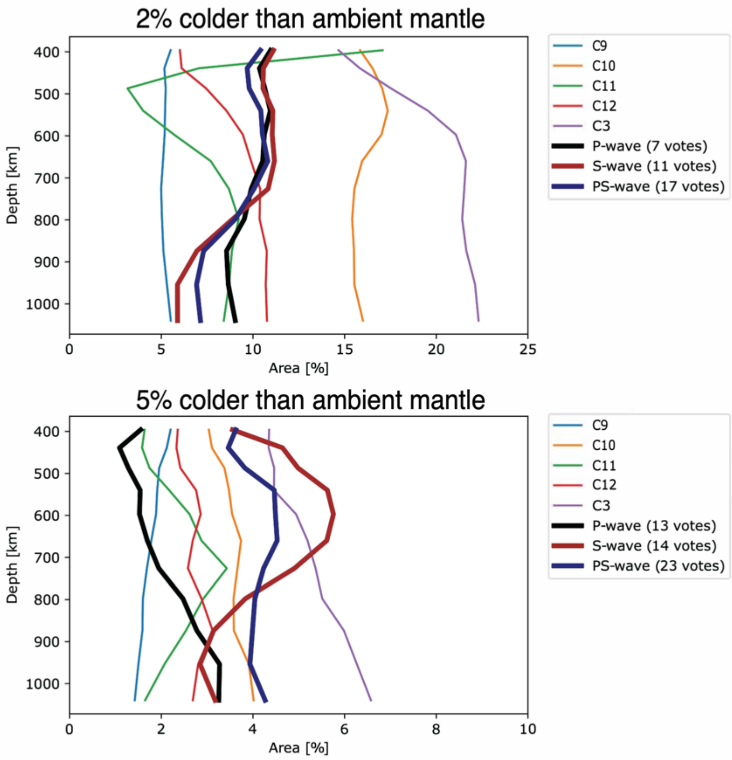


Figure 5. Global slab area as a function of depth for different thresholds in mantle flow models (defined as either 2% and 5% colder than ambient mantle) and tomographic vote maps (defined by the number of votes indicated in the legend out of 15 for P-wave models, 18 for S-waves models, and 33 for P- and S-wave models).

2.3.2. Quantitative spatial match between mantle flow and tomographic models

Visual comparison between mantle flow models and tomographic models reveals the spatial match between predicted present-day mantle temperatures and imaged seismic anomalies between 400 km depth and 1,000 km depth (Fig. 2).

We quantify the present-day match for slabs predicted by mantle flow models and imaged by vote maps of tomographic models. We use two quantities: 1/ the accuracy

$Acc = (TP + TN)/A$ which measures the ratio of the sum of true positive areas (TP) and true negative areas (TN) over the entire area (A) – this score is relatively large (Fig. 7) because TN is large (Fig. 6); and 2/ the sensitivity $S = TP/(TP+FN)$ which measures the ratio of TP over the sum of TP and false negative areas (FN) that represents the target area (mantle imaged to be seismically fast) – this score is relatively low (Fig. 7), reflecting that the target area (blue and orange in Fig. 6) is small (of the order of 4% of the total area, Fig. 5b).

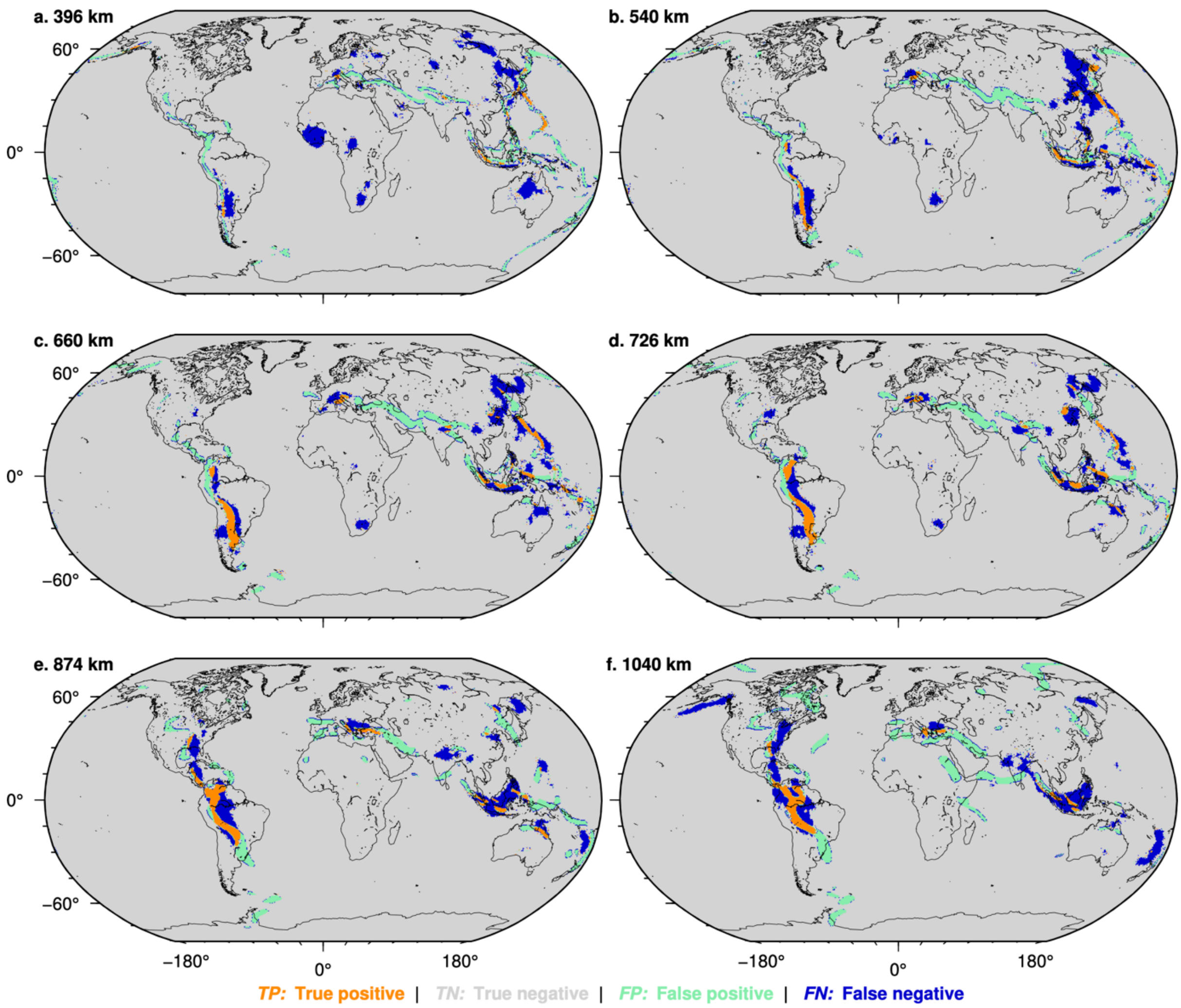


Figure 6. Spatial match between predicted cold lower-mantle and fast seismic anomalies in tomographic models. True positive *TP* areas (in orange) indicate predicted cold mantle and imaged seismically fast mantle, true negative *TN* areas (in grey) indicate that mantle is not predicted to be cold and imaged to be seismically fast, false positive *FP* areas (in green) indicate mantle predicted to be cold but imaged not to be fast, and false negative *FN* areas (in blue) indicate mantle not predicted to be cold but imaged to be fast. Present-day coastlines are shown in black. Results are shown at indicated depths for case C10, mantle 5% colder than ambient and 23 to 33 votes in the combined P- and S-wave vote map of fast seismic anomalies (Shephard et al. 2017).

To further investigate the sensitivity of the spatial match between predicted and imaged slabs, we jointly analyse cross-sections of mantle temperature and vote maps of tomographic models for three locations (Figs 8-10): the Mariana Trench characterised by a steeply dipping slabs that penetrates into the lower mantle (Jaxybulatov et al., 2013; Yang et al., 2019), the Farallon and Nazca plates under the Bolivian orocline of South America as another location featuring a slab that penetrates the lower mantle, although at a lower angle relative to the Mariana (Goes et al., 2008), and the Western Pacific plate characterised by a stagnating slab that lies along the boundary of the upper-lower mantle discontinuity (Li et al., 2008; Honda, 2016; Van der Meer et al., 2018). For each location, we investigate the sensitivity of predicted deep slab dip angles to specific input parameters.

2.4. Temporal evolution of predicted mantle slabs along selected cross-sections

Reconstructions of past mantle flow that best match tomography were selected to be analysed through time at three locations: the Mariana Trench back to 40 Ma or 50 Ma, the Bolivian orocline of South America and under Japan back to 80 Ma. The purpose of this analysis is to investigate the evolution of deep slab dip angles through time, as well as the sensitivity of the evolution of model deep slab dip angle to the input Rayleigh number and tectonic reconstruction used as boundary condition.

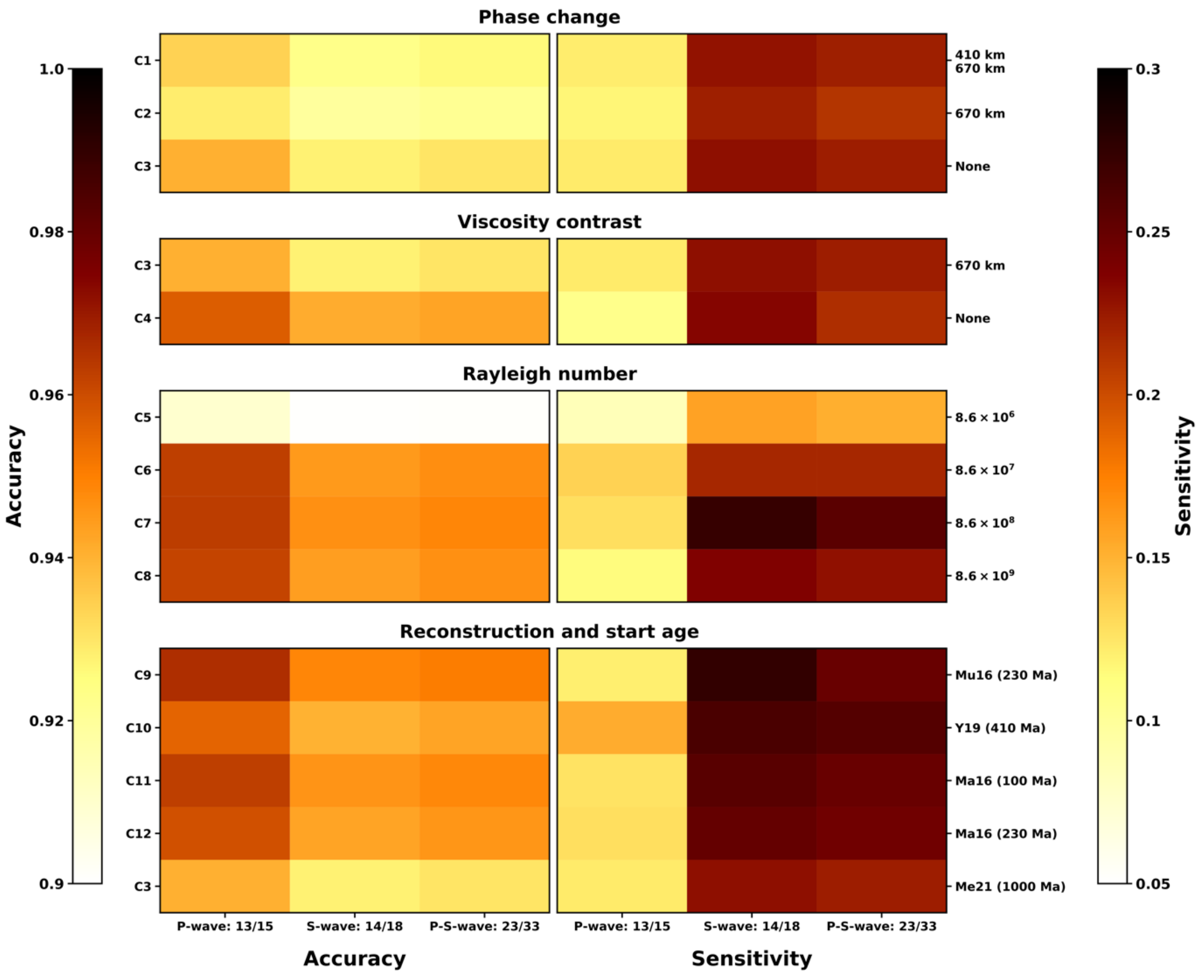


Figure 7. Quantitative match (accuracy on the left-hand-side and sensitivity on the right-hand-side) between mantle 5% colder than ambient and fast seismic anomalies in tomographic models. Different colour maps are used for accuracy and sensitivity. Mantle flow models have been grouped according to their input parameters.

2. Results

2.1. Effect of input parameters on the match to vote maps of tomographic models

We consider the effect of a phase change (cases C1-C3), the viscosity contrast at 660 km depth (cases C3 and C4), the Rayleigh number (cases C5-C8) and the reconstruction (cases C3 and C9-C12).

2.1.1. Phase Change

Cases C1-C3 only differ by the considered phase changes: in C1 there are two phase changes at 410 km and 660 km depths, in C2 one phase change at 660 km depth, and in C3 there is no phase change. For these cases, the match to tomographic models is generally good, with minor variations: the accuracy value averaged across tomographic models ($\overline{Acc}$) is 93%, 92% and 92% for C1, C2 and C3 respectively, and the sensitivity value averaged across tomographic models ($\bar{S}$) is 19%, 18% and 19% for C1, C2 and C3 respectively (Fig. 7).

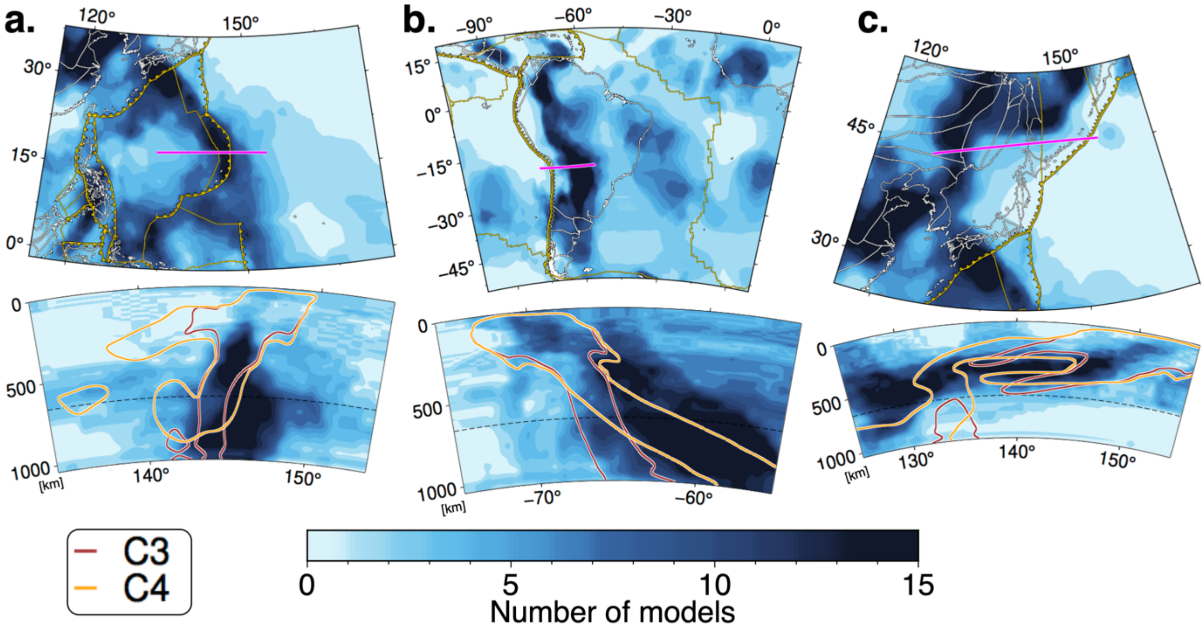


Figure 8. Vote maps for 15 global P-wave tomographic models. (a) Map at 660 km depth and cross-section for the Mariana Trench. (b) Map at 660 km depth and cross-section for South America. (c) Map at 660 km depth and cross-section around Japan. The colour palette is saturated for 13 or more models. On the cross-sections, maroon and orange contours represent models C3 and C4. On the maps, golden lines represent plate boundaries (subduction zone polarities are indicated by symbols), white lines represent coastlines and the transect is shown in magenta. All mantle flow model contours are taken for mantle 5% colder than ambient. The dashed lines on the cross-sections are at 660 km depth.

2.1.2. Viscosity contrast at 660 km depth

Cases C3 and C4 only differ by the viscosity contrast at 660 km depth: in case C3 the viscosity pre-factor is ten times greater in the lower mantle than in the upper mantle, whereas it is the same in the upper mantle and lower mantle in case C4. The match to tomographic models was again generally good and similar for these models, with $\overline{Acc}$ equal to 93% and to 95% for cases C3 and C4, respectively, and $\bar{S}$ = 19% for both cases. Cross-sections reveal that slabs dip more steeply into the lower mantle for case C4 than for case C3, as expected from the absence of viscosity contrast; this results in an improved visual match for the Mariana slab that is steeply dipping (Fig. 8a), however, in a poorer match for the Farallon and Nazca slab under the Bolivian orocline of South America that penetrates into the lower mantle at a shallower angle (Fig. 8b) and for the Western Pacific slab that stagnates atop the lower mantle (Fig. 8c).

2.1.3. Rayleigh number

Cases C5-C8 only differ by the Rayleigh number, which is equal to 8.60×10^6 in case C5, 8.60×10^7 in case C6, 8.60×10^8 in case C7, and 8.60×10^9 in case C8. The match to seismic tomographic models is very sensitive to the Rayleigh number. $\overline{Acc}$ and $\bar{S}$ are smallest for case C5, increase as the Rayleigh number is increased to 8.60×10^7 (C6) or 8.60×10^8 (C7), and then decrease again (Fig. 7). $\overline{Acc}$ is equal to 95% for cases C6 and C7, and $\bar{S}$ is equal to 19% and to 21% for cases C6 and C7, respectively (Fig. 7). While the match remains high for $Ra = 8.60 \times 10^9$ (case C8, $\overline{Acc}$ = 95% and $\bar{S}$ = 19%), cross-sections show that the angle of penetration of the slab into the lower mantle increases with the Rayleigh number (Fig. 9). Consequently, C8 slabs best match tomographic model votes on the cross-sections for the steeply dipping Mariana slab, for which C5 slabs are the worst match and C6 and C7 slabs fall in between (Fig. 9a); C8 slabs show the poorest match to the stagnating Western Pacific plate, for which cases C5-C7 predict a stagnating slab (Fig. 9c). Visually, the deep slab dip angles for cases C6 and C7 better matches tomographic models than that for slabs C8 and C5 (Fig. 9b). Overall, our preferred Rayleigh number is 8.60×10^8 (C7), which results in good matches to tomographic models globally (Figs 5 and 6) and regionally (Fig. 9), and has been shown to predict slab sinking rates consistent with tomographic constraints (Flament, 2019).

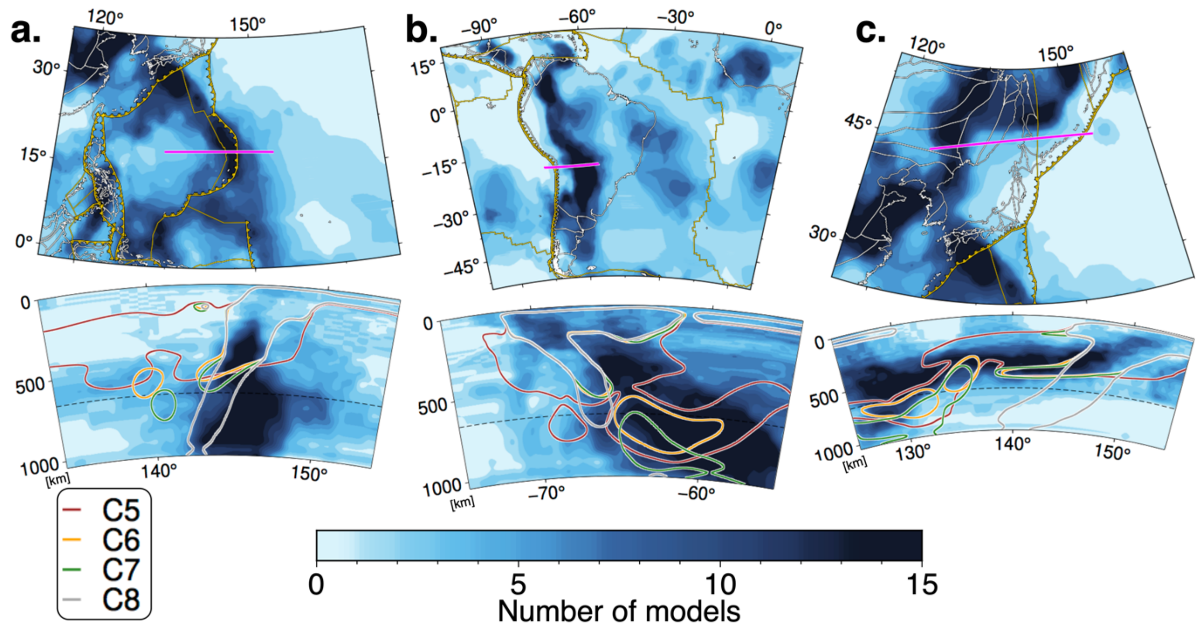


Figure 9. Vote maps for 15 global P-wave tomographic models. (a) Map at 660 km depth and cross-section for the Mariana Trench. (b) Map at 660 km depth and cross-section for South America. (c) Map at 660 km depth and cross-section around Japan. The colour palette is saturated for 13 or more models. On the cross-sections, maroon, orange, green and grey contours represent models C5, C6, C7 and C8 respectively. On the maps, golden lines represent plate boundaries (subduction zone polarities are indicated by symbols), white lines represent coastlines and the transect is shown in magenta. All mantle flow model contours are taken for mantle 5% colder than ambient. The dashed lines on the cross-sections are at 660 km depth.

2.1.4. Tectonic reconstruction

We varied the tectonic reconstruction used as surface boundary condition across mantle flow model cases C3 and C9-C12 (Table 1). The model start age a_0 was also varied across these model cases between 100 Ma and 1000 Ma (Table 1); while a_0 should be greater than ~250 Ma to investigate predicted deep mantle structure (Flament, 2019), a_0 = 100 Ma is sufficient for slabs to sink down to 1000 km depth with the selected Rayleigh number and viscosity structure (Flament, 2019). For these cases, 93% < $\overline{Acc}$ < 95% with a maximum for C9 (Fig. 7), and 19% < $\overline{S}$ < 22% with a minimum for C3 and a maximum for C10 (Fig. 7). At the three considered locations, this series of cases generally matches tomographic models, although with some variability in the prediction of slab material between model cases (Fig. 10). Cases C3 (based on reconstruction Me21) and C10 (based on reconstruction Y19) generally predict similar deep slab dip angles, which is expected since reconstruction Me21 extends reconstruction Y19 further back in time, although Case C3 tends to predict a greater amount of slab material in the upper mantle compared to other cases. Both cases match tomographic models at locations with penetrating and stagnating slabs (Fig. 10). Cases C9 (Mu16) and C12 (Ma16) also share similarities with each other, notably predicting slab break offs at approximately 660 km depth (Fig. 10); C9 predicts slabs that penetrate more steeply into the lower mantle due to the absence of a viscosity contrast. Out of these cases, C11 (Ma16) predicted the thinnest slabs and the most rapid changes in dip angle between 650 km depth and 900 km depth, including a prominent slab break off and offset at the Mariana Trench, which is not consistent with tomographic models (Fig. 10a). Overall, case C10 is preferred, because it predicts slabs that best match tomographic vote maps globally, and with geometries compatible with tomographic models at the three selected locations.

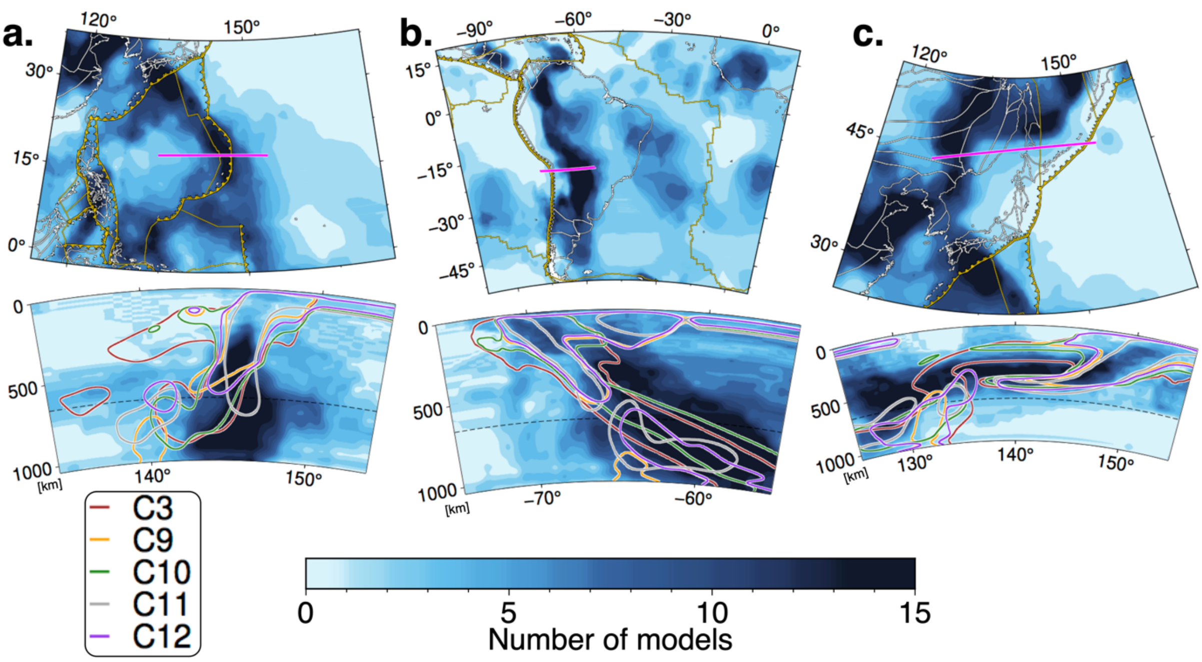


Figure 10. Vote maps for 15 global P-wave tomographic models. (a) Map at 660 km depth and cross-section for the Mariana Trench. (b) Map at 660 km depth and cross-section for South America. (c) Map at 660 km depth and cross-section around Japan. The colour palette is

saturated for 13 or more models. On the cross-sections, maroon, orange, green, grey and purple contours represent models C3, C9, C10, C11 and C12 respectively. On the maps, golden lines represent plate boundaries (subduction zone polarities are indicated by symbols), white lines represent coastlines and the transect is shown in magenta. All mantle flow model contours are taken for mantle 5% colder than ambient. The dashed lines on the cross-sections are at 660 km depth.

2.2. Evolution of predicted deep slab dip angles through time

We analyse the evolution of predicted deep slab dip angles for preferred case C10 for models with contrasted Rayleigh number and input tectonic reconstruction because these were found to be the two factors that most affected present-day deep slab dip angle in the previous section.

2.2.1. Effect of the Rayleigh number

The match between mantle flow models and tomographic models is very sensitive to the Rayleigh number (Fig. 7). Here, we investigate the evolution of predicted deep slab dip angles for continuous subduction at the Mariana Trench from 48 Ma (Fig. 11) and under Japan from 79 Ma (Fig. 12) for model cases based on contrasted Rayleigh numbers. Maps of mantle temperature at 660 km depth give a sense of the deep slab dip angles in the upper mantle: because subduction zones exist for the entire period represented on the figure, larger distances between the trench (in green with symbols for polarity, at the surface) and cold temperature anomalies at 660 km indicate that the trench has rolled back since the slab was anchored into the lower mantle (Figs 11 and 12). Cross-sections in the mantle frame of reference (i.e., not moving with plates) show that the Mariana Trench rolled back between 48 Ma and 28 Ma and has been largely stable from 28 Ma (Fig. 11). In contrast, subduction of the Izanagi and Western Pacific plate to the north of the Japanese Islands was stable between 79 Ma and 58 Ma and rolled back in the last 18 Myr (Fig. 12). Our results indicate that trench motion affects deep slab dip angle.

At the Mariana Trench, C8 slabs (largest *Ra*) penetrate the lower mantle at a high angle by 28 Ma, and this behaviour persists until the present day with a minor slab break off event at 8 Ma (Fig. 11). In contrast, C5 slabs (lowest *Ra*) have accumulated in the upper mantle and stagnated atop the lower mantle from 28 Ma (Fig. 10), which is not consistent with tomographic models (Fig. 9). Cases C6 and C7 predict a slab break-off from 8 Ma, with penetration into the lower mantle in the last 8 Myr, offset westward from the trench (Fig. 11), which is not consistent with tomographic models either (Fig. 9).

To the north of the Japanese Islands, the Izanagi slab dipped at ~60º in the upper mantle between 79 Ma and 58 Ma, and the dip angle into the lower mantle was variable: it was steep for case C8 (largest *Ra*) at 79 Ma and 58 Ma, and steepened from a shallow dip between 79 Ma and 58 Ma for all other cases (Fig. 12). As the trench rolled back, the dip angle decreased in the upper mantle for cases C5-C7, however, the dip angle into the lower mantle remained large for case C8 (largest *Ra*) so that the slab penetrates the lower mantle without stagnating into the upper mantle at present day, which is not consistent with tomographic models (Fig. 9). Case C5 (smallest *Ra*) predicts the largest offset between the trench and penetration into the lower mantle, although this offset is still smaller than in tomographic models (Fig. 9). Cross-sections of tomographic votes suggest that the volume of stagnating slabs is between that predicted by case C5 and by cases C6 and C8 (Fig. 9), although this visual comparison depends on selected thresholds (Fig. 6). Overall, these results suggest that the Rayleigh number alone cannot be adjusted to fit contrasted deep slab dip angles, and that regional variations in the viscosity structure of the mantle could account for imaged deep slab dip angles.

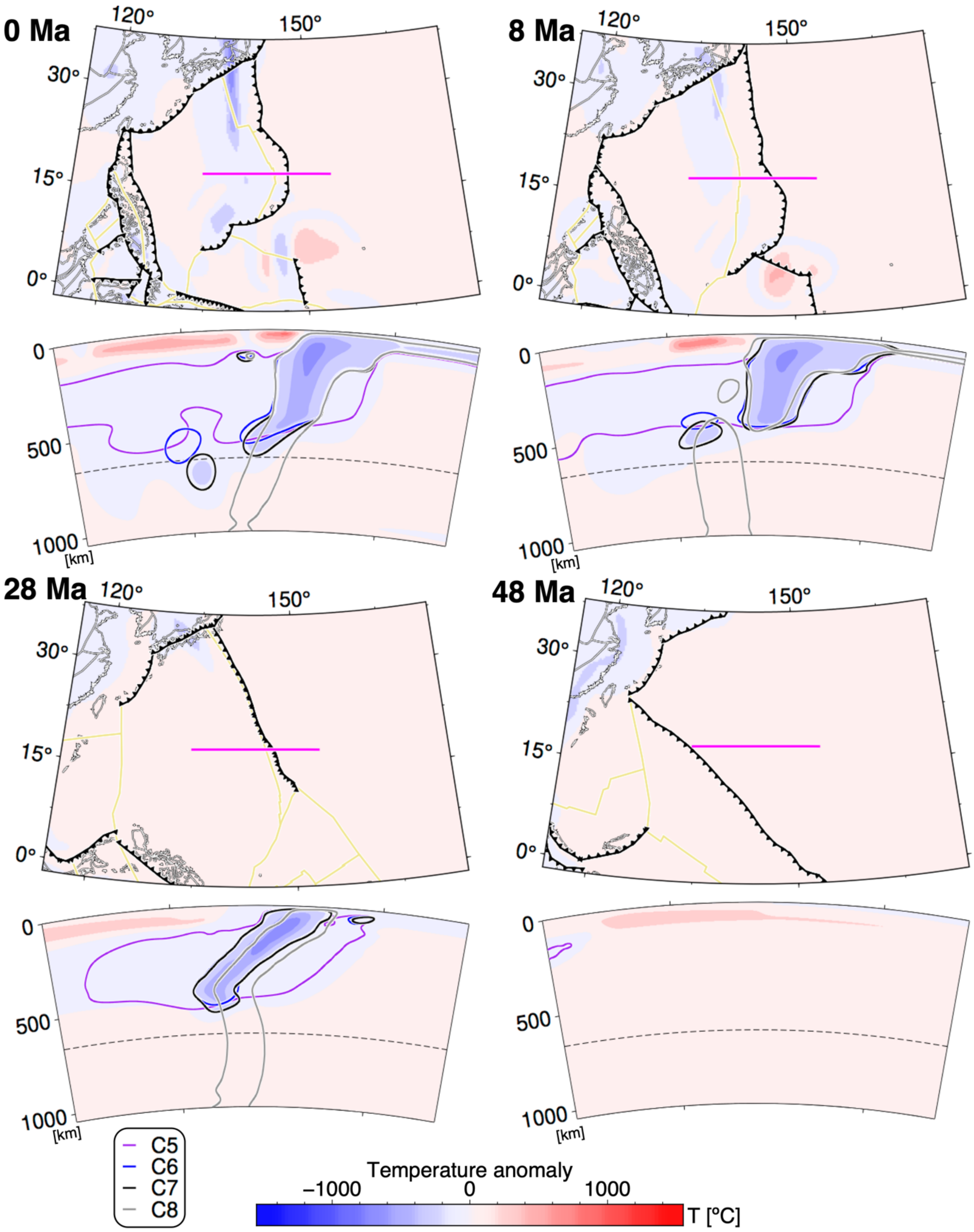


Figure 11. Cross-sections of mantle flow models based on different Rayleigh numbers through time, taken under the Mariana Trench. Purple, blue, black and grey contours on cross-sections represent models C5, C6, C7 and C8 (note that C8 is shown at 0 Ma, 9 Ma, 29 Ma and 48 Ma, resulting in a slight offset). The predicted mantle temperature anomaly is shown at 660 km depth for C7. On the maps, black lines represent subduction zones, grey lines represent coastlines, khaki lines represent mid-ocean ridges and transform faults, and magenta line the location of the cross-section. The dashed lines on the cross-sections are at 660 km depth.

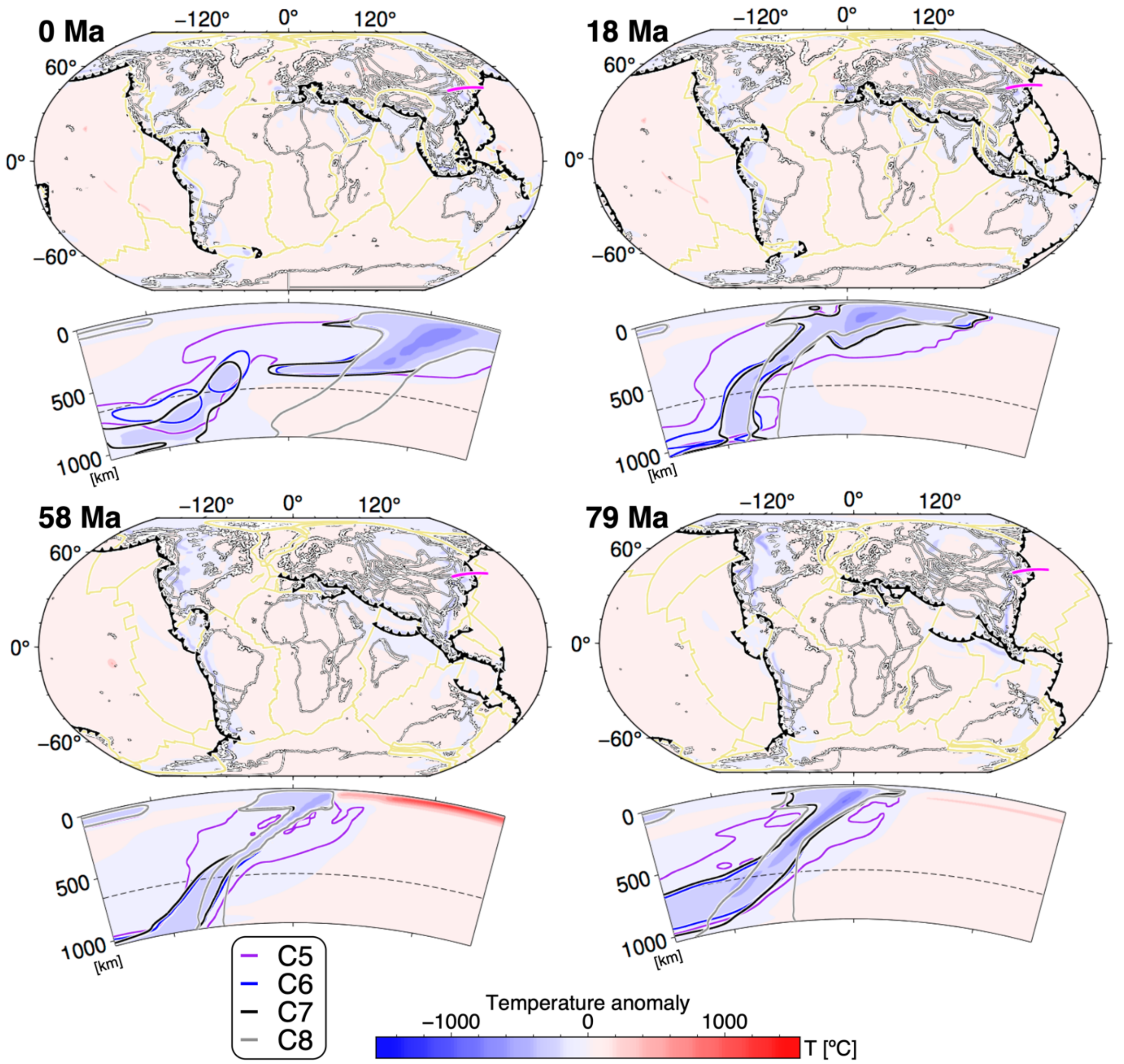


Figure 12. Cross-sections showing the evolution of temperature predicted by mantle flow models based on different Rayleigh numbers, taken under Japan. Purple, blue, black and grey contours on cross-sections represent models C5, C6, C7 and C8 (note that C8 is shown at 0 Ma, 19 Ma, 59 Ma and 78 Ma, resulting in a slight offset). The predicted mantle temperature anomaly is shown at 660 km depth for C7. On the maps, black lines represent subduction zones, grey lines represent coastlines, khaki lines represent mid-ocean ridges and transform faults, and magenta line the location of the cross-section. The dashed lines on the cross-sections are at 660 km depth.

2.2.2. Effect of the tectonic reconstruction

The subduction history is overall very similar in cases C9 (reconstruction Mu16), C10 (reconstruction Y19) and C12 (reconstruction Ma16); trenches in reconstructions Mu16 and

Ma16 are near identical, with differences at ~19 Ma in Southeast Asia and along the Arabian Peninsula (Fig. 14), and more significant differences at 79 Ma for the configuration of subduction between India and Asia and along Oman (Fig. 14). There are more differences between reconstructions Y19 and Mu16, which reflect 1/ the use of different reference frames: Torsvik et al. (2008) in Mu16, and Torsvik and Voo (2002) in Y19, 2/ the use of deforming plate boundary zones (Müller et al., 2019) in the versions of tectonic reconstructions Mu16 and Ma16 presented here, but not in reconstruction Y19 – this effect is most prominent for South America at 79 Ma (Fig. 13) – , 3/ as well as differences in relative plate motions: reconstruction Y19 includes a slab to the east of the Arabian Peninsula at 79 Ma to account for the emplacement of the Oman ophiolite (Searle and Cox, 2002), two subduction zones between India and Eurasia (Jagoutz et al., 2015), and differences in the subduction history to the North of Australia and around the Philippine Sea plate (Zahirovic et al., 2016).

At the Mariana Trench, results for all three model cases are similar at 39 Ma and at 29 Ma (Fig. 13). At 9 Ma, the slab is further to the east in C10 (Y19) than in C9 (Mu16) and C12 (Ma16), and because this location is more similar to the present-day location of the trench, this results in a C10 slab that is continuous and steeply dipping into the lower mantle at present-day (Fig. 13), which is consistent with tomographic models (Fig. 10), whereas C9 and C12 slabs are not continuous and offset with respect to tomographic models (Figs 10 and 13). The C9 slab dips more steeply into the lower mantle than the C12 slab, which is expected in the absence of a viscosity contrast at 660 km depth in C9 (Table 1). The slab volume is greater in C10 than in C9 and C12 because the thickness of the oceanic lithosphere and shallow slabs was built with a half-space cooling assuming a maximum lithospheric age of 80 Ma in C9 and C12, and without a maximum in C10.

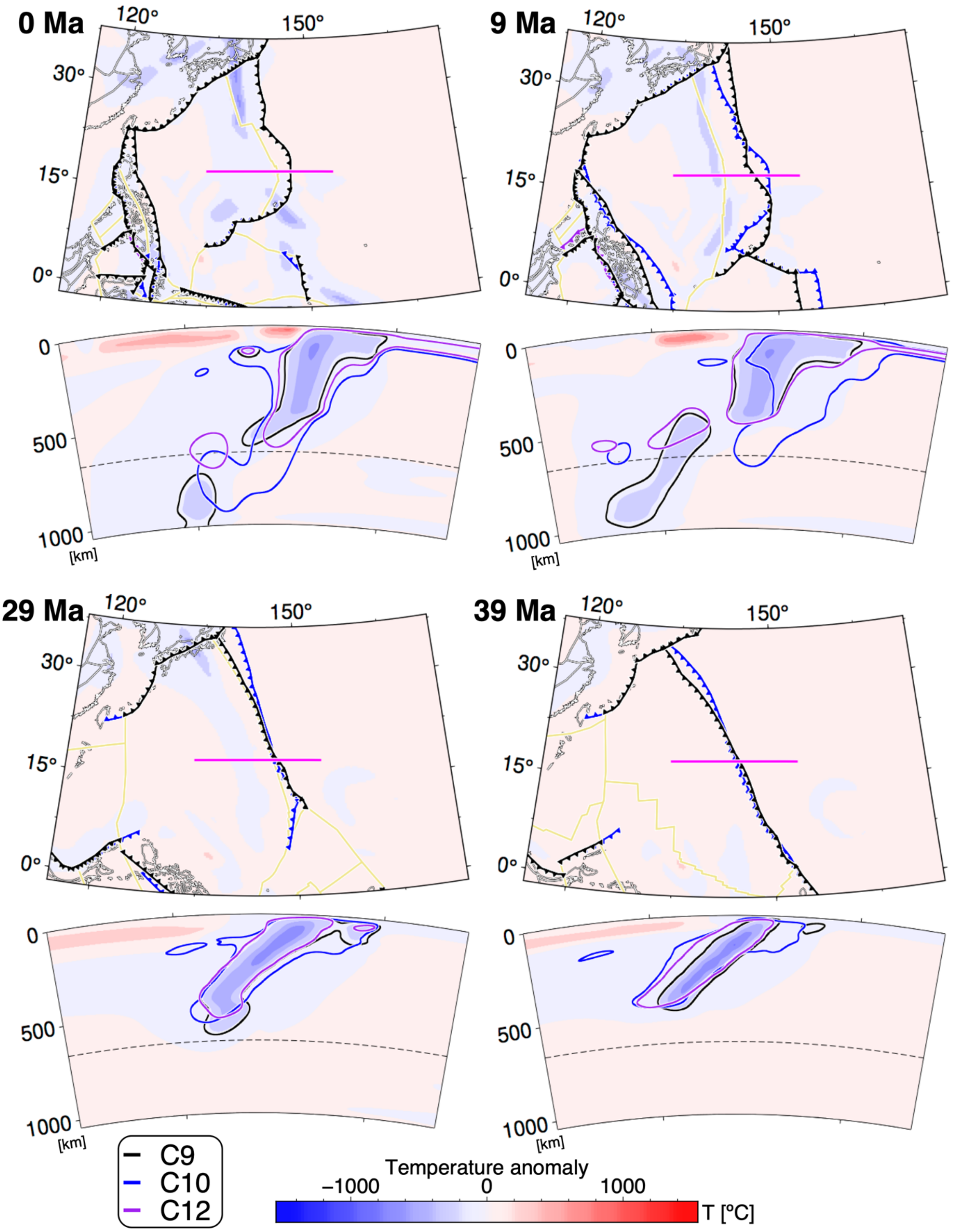


Figure 13. Cross-sections showing the evolution of temperature predicted by mantle flow models based on different tectonic reconstructions, taken under the Mariana Trench. Black, blue and purple contours on the cross-sections represent models C9, C10 and C12 respectively. The predicted mantle temperature anomaly is shown at 660 km depth for C9. On the maps, black, blue and purple lines represent subduction zones for models C9, C10 and C12

respectively. Grey lines represent coastlines, khaki lines represent mid-ocean ridges and transform faults for case C9, and magenta line the location of the cross-section. The dashed lines on the cross-sections are at 660 km depth.

Differences between cases C9, C10 and C12 are smaller the north of the Japanese Islands. At 79 Ma, the trench is slightly offset to the east in C10 compared to C9 and C12, slab dip angles are similar across cases in the upper mantle, and steeper for C9 in the lower mantle in the absence of a viscosity contrast. All three cases are similar at 29 Ma, with a ~60º dip in the upper mantle that steepens to ~80º in the lower mantle for cases C10 and C12 whereas slab C9 is broken off at ~950 km depth. The lateral offset between the trench and the anchor point in the lower mantle increases from 29 Ma to the present in all three models, and while the stagnation in the upper mantle is consistent with tomographic models, the lateral offset between the trench and the entry point into the lower mantle is smaller in all three cases than in tomographic models, and the slab is continuous in tomographic models whereas it is not in the flow models (Figs 10 and 14). These two features suggest that changes to tectonic reconstructions of this area may be required: the slab breakoff in the models (Figs 10 and 14) suggests that the subduction rate is too small with respect to the trench rollback, and the larger lateral offset in tomographic models than in flow models (Fig. 10) suggests that the trench should initially be ~100 km further west back in time (at ~80 Ma), which would lead to the slab anchoring into the lower mantle further west (Fig. 14) and to trench rollback over a greater distance but also over a longer period.

2.2.3. Tectonic origins of penetrating and stagnating slabs

The shape of the reconstructed Mariana Trench changed from a near straight subduction zone between 49 Ma and 29 Ma, to a curved trench system in the last 19 Myr. The trench rolled back between 49 Ma and 29 Ma and it has been largely stable since then, which for case C10 leads to the development of a continuous slab that dips steeply into the upper mantle then shallowing into the top of the upper mantle (Figs 13 and 15). This prediction is generally consistent with tomographic models, although the imaged slab penetrates the lower mantle at a steep angle, and down to 1000 km as opposed to ~950 km depth (Fig. 10).

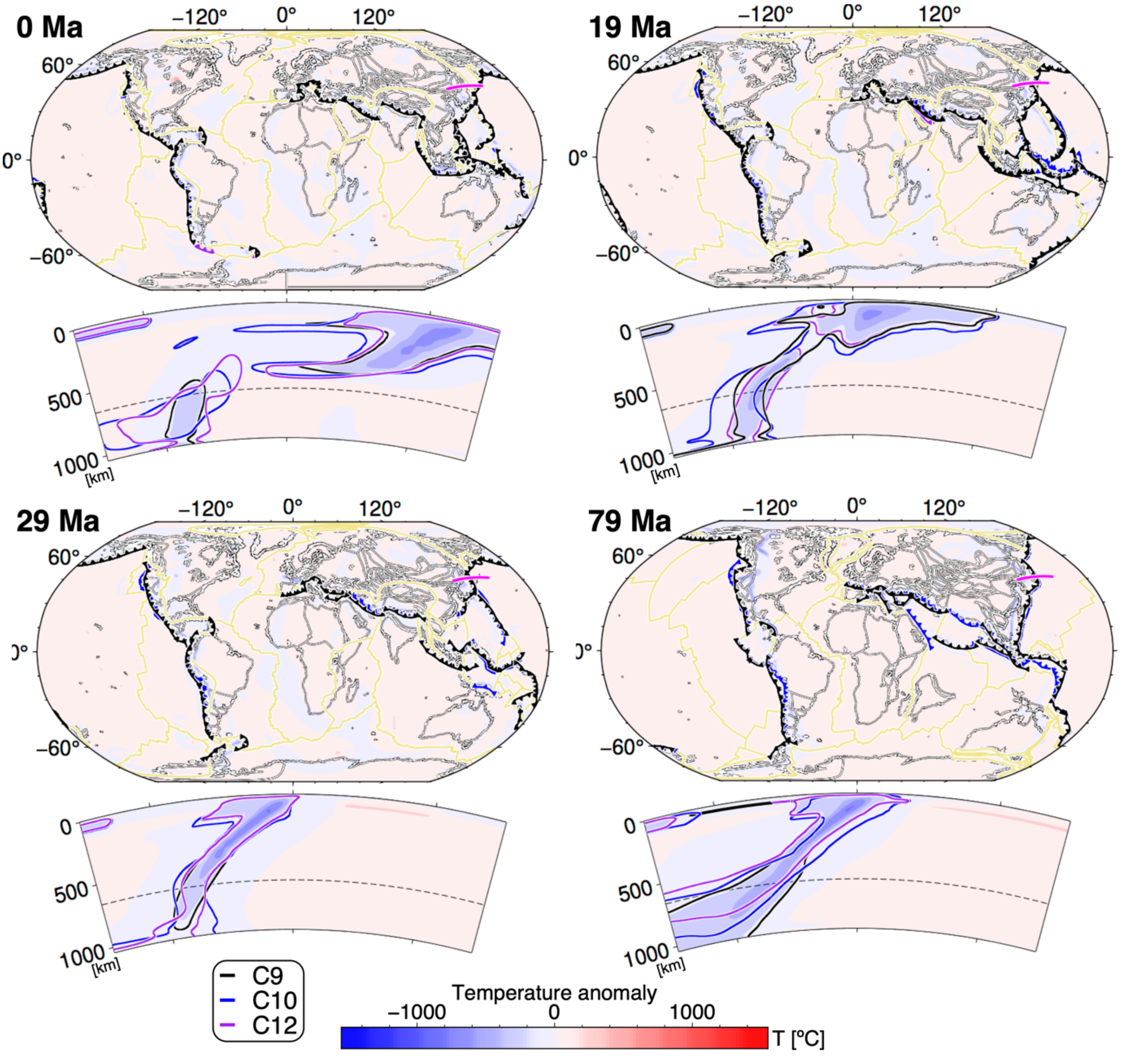
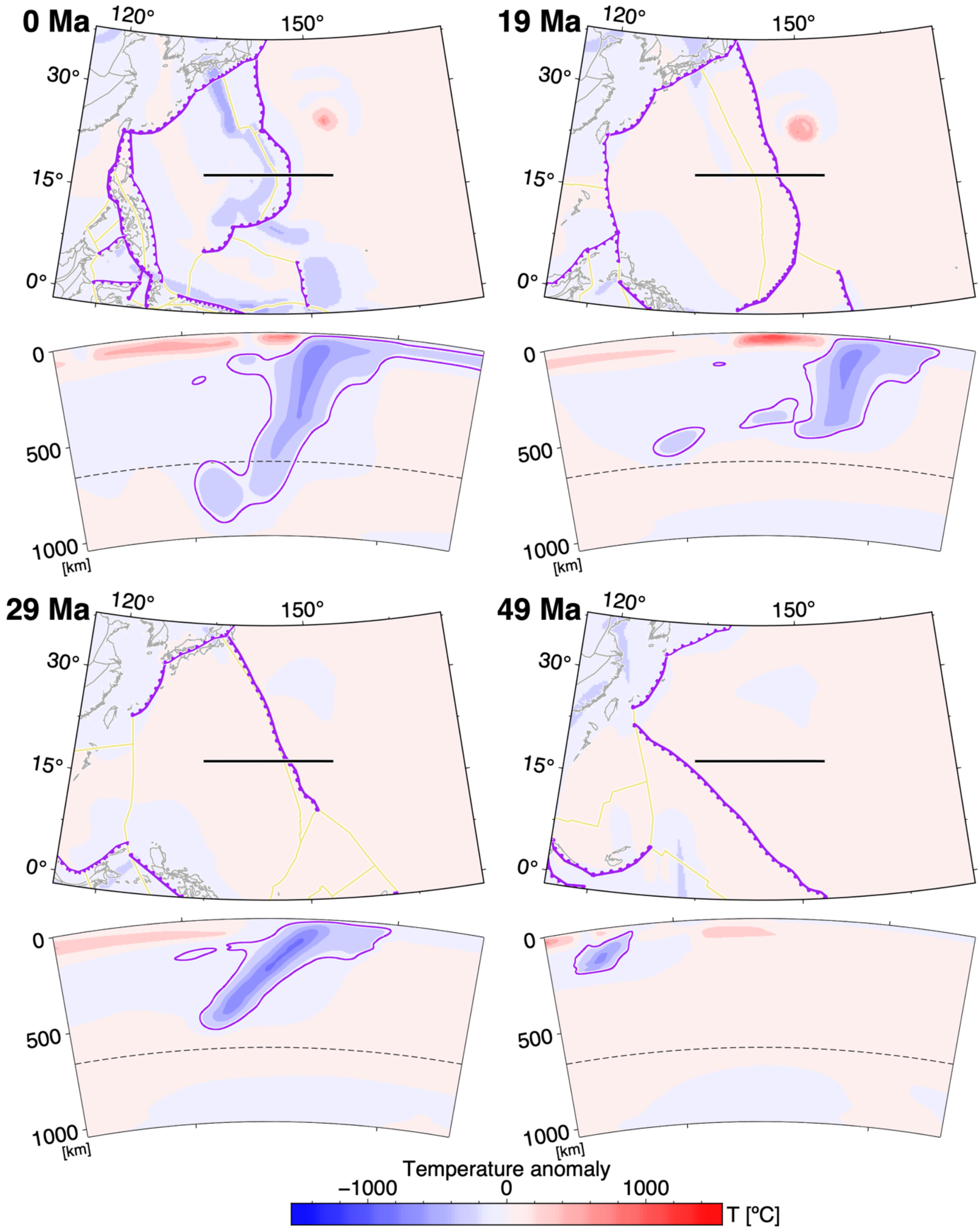


Figure 14. Cross-sections showing the evolution of temperature predicted by mantle flow models based on different tectonic reconstructions, taken under Japan. Black, blue and purple contours on the cross-sections represent models C9, C10 and C12 respectively. The predicted mantle temperature anomaly is shown at 660 km depth for C9. On the maps, black, blue and purple lines represent subduction zones for models C9, C10 and C12 respectively. Grey lines represent coastlines, khaki lines represent mid-ocean ridges and transform faults for case C9, and magenta line the location of the cross-section. The dashed lines on the cross-sections are at 660 km depth.

In reconstruction Y19 that does not account for deformation, the South American trench along the Bolivian orocline retreated by ~19º westward since 79 Ma from ~52ºW to ~71ºW (Fig. 16); the total amplitude of this retreat would be smaller in models accounting for Andean mountain building (Fig. 14; Müller et al., 2019). The point of slab penetration into the lower mantle migrated by ~16º over the same period, from ~48ºW to ~64ºW, leading to a shallowing of the slab over time, which is more pronounced in the lower mantle than in the upper mantle: At 49 Ma, the predicted slab dipped at ~60º down to 1000 km depth; by 29 Ma, the slab bent into the lower mantle, and at 0 Ma, the slab dips at ~50º in the upper mantle and ~30º in the lower mantle (Fig. 16). Tomographic models suggest that the slab dips steeply into the lower mantle, which is more consistent with tectonic reconstructions that account for the deformation of the South American continent (e.g., case C12 in Fig. 10b).

To the north of the Japanese Island, the trench is reconstructed to have been largely stable between 79 Ma and 29 Ma, and to have retreated in the last 19 Myr. The slab predicted for case C10 penetrated into the lower mantle at 79 Ma with a dip of ~60º down to 660 km depth and stagnation further west (dip ~0º) at ~900 km depth; at 29 Ma the dip was ~60º in the upper mantle and nearly vertical into the lower mantle; at 19 Ma the dip was ~50º in the upper mantle and vertical into the lower mantle, and at present-day the slab stagnates in the lower mantle and in the uppermost lower mantle. These results illustrate the effect of trench retreat on deep slab dip angle. As mentioned above, revisiting the initial location of the Izanagi and Western Pacific trench and the timing of trench retreat could improve the match between mantle flow models and tomographic models at this location (Fig. 10).



608 **Figure 15.** Cross-sections of model C10 through time, taken under the Mariana Trench. The
609 top panels show the regional reconstruction for the Mariana Trench through time. The predicted
610 mantle temperature anomaly is shown at 660 km depth for C10. Purple lines represent
611 subduction zones, grey lines represent coastlines, and khaki lines represent mid-ocean ridges
612 and transform faults.
613

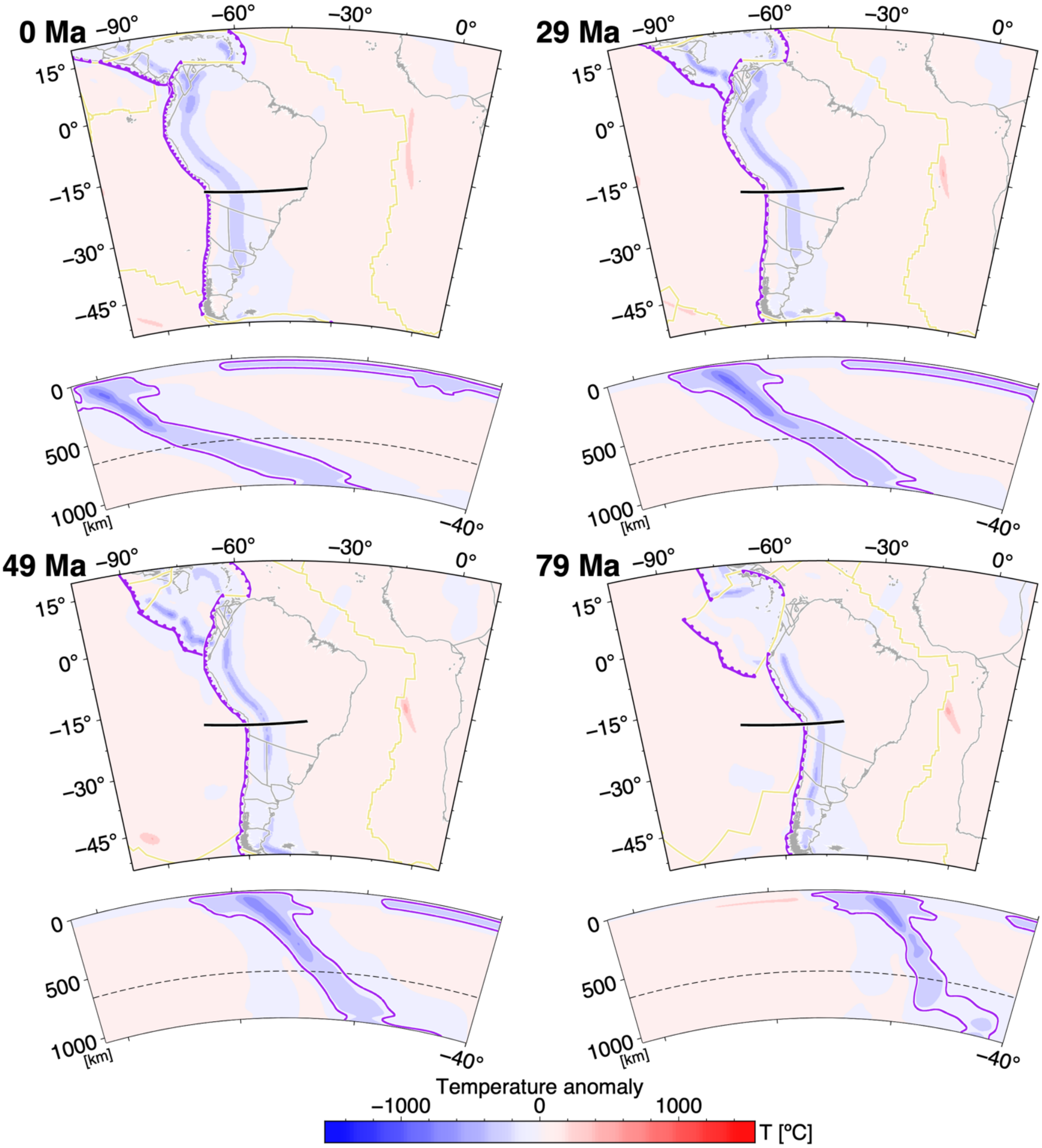


Figure 16. Cross-sections of C10 through time, taken under South America. The top panel shows the regional reconstruction for South America through time. The predicted mantle temperature anomaly is shown at 660 km depth for C10. Purple lines represent subduction zones, grey lines represent coastlines, and khaki lines represent mid-ocean ridges and transform faults.

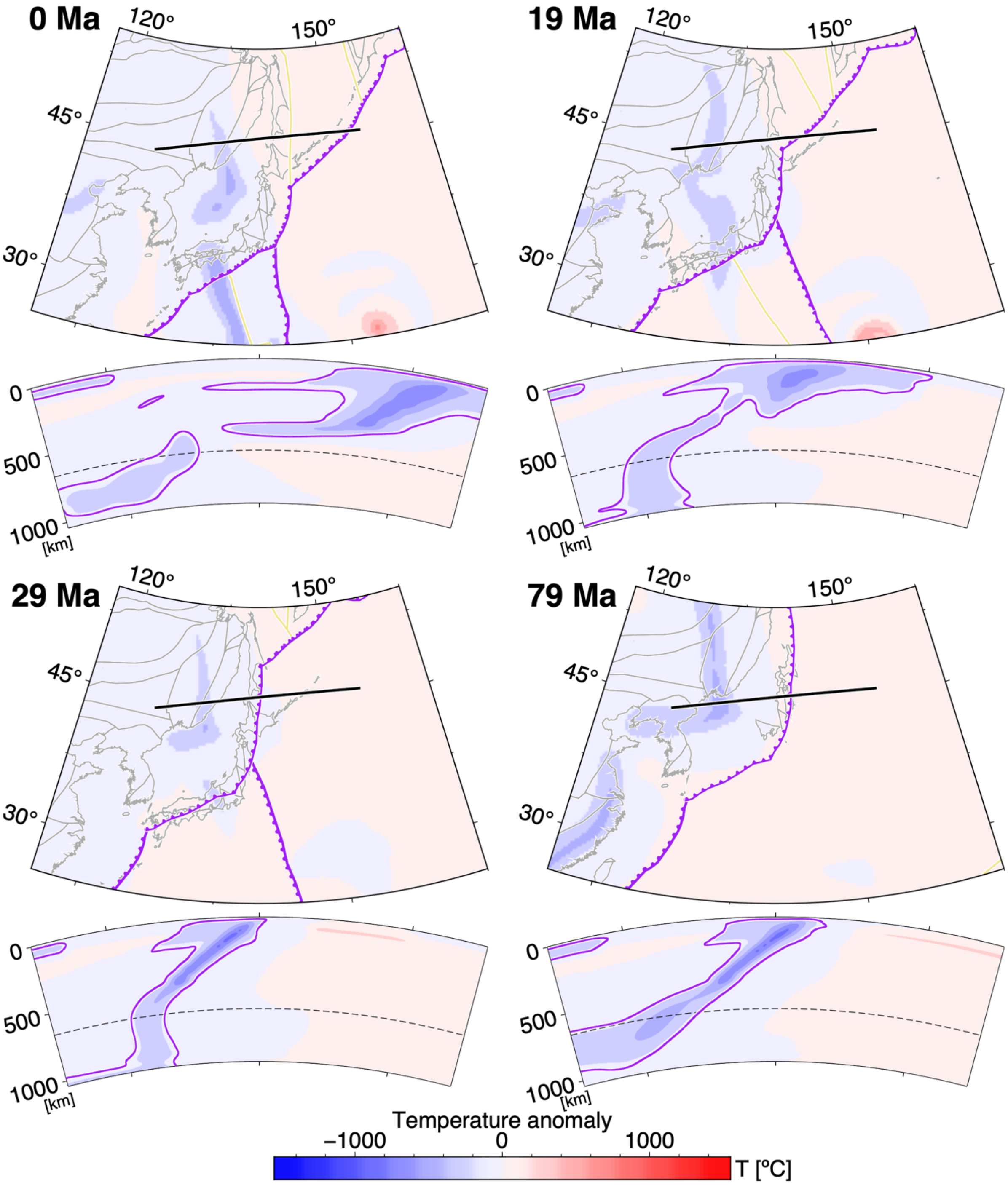


Figure 17. Cross-sections of model C10 through time, taken under Japan. The top panel shows the regional reconstruction for East Asia through time. The predicted mantle temperature anomaly is shown at 660 km depth for C10. Purple lines represent subduction zones, grey lines represent coastlines, and khaki lines represent mid-ocean ridges and transform faults.

3. Discussion

4.1. Factors contributing to deep slab dip angle

The main factors affecting deep slab dip angle that were investigated in this study were phase changes, the viscosity contrast at 660 km depth, the Rayleigh number and the tectonic reconstruction.

3.1.1. Phase change.

We found that considering phase changes at 410 km and 660 km depth only has a minor effect on model results. Agrusta et al. (2017) used fully dynamic models to show that phase transitions affect the evolution of deep slab dip angle through time. This difference could reflect that imposing surface plate velocities and the thermal structure of slabs down to 350 km controls mantle dynamics down in our models. Because large-scale mantle flow influences the location and deep dip angle of slabs (Peng and Liu, 2023), we suggest that the effect of phase changes on the interaction of slabs with the transition zone could be investigated in fully-dynamic global convection models (e.g., Coltice et al., 2019).

3.1.2. Viscosity contrast at 660 km depth.

We found that the presence of a viscosity increase at 660 km depth was required to explain stagnating slabs, consistently with previous work (e.g., Čížková and Bina, 2019). An increase by a factor of ten was sufficient for slabs to stagnate, although viscosity also increases with pressure (and therefore depth) in our models. In the absence of a viscosity increase with depth, all slabs dip steeply into the lower mantle which does not match tomographic constraints (Fig. 8). We did not investigate the effect of a thin low-viscosity layer beneath the transition zone which has been proposed to favour slab stagnation and improve the qualitative match between slabs predicted by tectonically-driven mantle flow models and imaged by tomographic models (Mao and Zhong, 2018). We find that slab stagnation occurs in our models in the absence of a low-viscosity layer beneath the transition zone (Figs 8-10, 12, 14) and note that the models of Mao and Zhong (2018) used the Boussinesq approximation, which is known to result in excessive slab volume (Flament, 2019). The effect of a thin low-viscosity layer beneath the transition zone on slab stagnation could be investigated in future models using the extended-Boussinesq or truncated anelastic liquid approximation.

3.1.3. Rayleigh number.

The Rayleigh number affects the vigour of convection, and in turn the dip angle of slabs: models with a large Ra = 8.60×10^9 resulted in slabs penetrating the lower mantle nearly vertically, while models with a low Ra = 8.60×10^6 resulted in slabs stagnating in the upper mantle (Figs 9, 11 and 12). Intermediate deep slab dip angles were obtained for $8.60 \times 10^7 < Ra < 8.60 \times 10^8$. The Rayleigh number influences the slab sinking rate and the CMB heat flow (because Ra is proportional to the temperature drop across the mantle ΔT). Flament (2019) compared these two metrics to independent constraints and preferred model cases with Ra = 8.60×10^8.

3.1.4. Tectonic reconstruction and trench motion.

Previous work has shown that fast trench motions (2-4 cm/yr) can cause a slab to flatten at the upper-lower mantle boundary (van der Hilst and Seno, 1993; Griffiths et al., 1995; Christensen, 1996; Olbertz et al., 1997) and that in contrast, limited trench retreat can result in the penetration of a slab through this 660 km discontinuity, sinking through to the lower mantle (van der Hilst and Seno, 1993). Our models confirm these findings: we find that the stability of the Mariana Trench leads to steeply dipping slab, whereas the fast retreat of the trench to the east of Japan over the last 19 Myr leads to the stagnation of the Pacific slab atop the upper mantle following a period during which the slab penetrated into the lower mantle when the trench was stable (79 Ma – 29 Ma). The scenario along South America also illustrates how changes in trench motion are reflected in deep slab dip angles, with trench retreat leading to a shallowing of the dip angle in the upper mantle (in the flow models). Trench retreat may lead to slab break off (Fig. 17), and we find that the retreat of the Izanagi and Western Pacific trench should start further west than in the reconstruction to match the anchoring of the slab and occur at a lower rate (over a longer period) to avoid slab breakoff since this is not imaged by tomographic models (Fig. 10c). Indeed, recent studies have used mantle tomography (Wu et al., 2022) or mantle flow models (Ma et al., 2019) to improve tectonic reconstructions for East Asia for the last ~120 Myr.

Further potential contributing factors to deep slab dip angles include slab age and subduction velocity (e.g., Goes et al., 2017). While these factors are more tractable in two-dimensional subduction models than in our global reconstructions of past mantle flow, they could be investigated in future investigations of our models.

4.2. Strengths and limits of our approach

4.2.1. Mantle flow models

The mantle flow models used in this study can be directly compared to independent spatial constraints on mantle convection because they use tectonic reconstructions as boundary conditions to simulate past mantle convection. Here, we compare the present-day temperature predicted by our forward mantle flow models to tomographic models from which they are mostly independent. The initial temperature structure of our forward mantle flow models is not derived from tomographic models. In this respect, our reconstructions of mantle flow are independent from tomographic models, compared to approaches that use tomographic models to model mantle flow (e.g., Steinberger and Calderwood, 2006). In our models, in order to obtain one-sided subduction with lateral resolution ~50 km and lateral viscosity variations over three orders of magnitude, the shallow portion of subducting slabs is calculated analytically and blended in with the solution for mantle convection down to ~ 350 km depth, making it possible to quantitatively compare mantle flow and tomographic models between 396 km and 1,040 km depths.

A separate approach imposing plate velocities, the thermal structure of the lithosphere, as well as viscosity and buoyancy variations in the vicinity of subduction zones makes it possible to predict the shallow slab dip angle in mantle flow models extending back ~150 Ma (Hu et al., 2018). Yet another approach consists of investigating the deep slab dip angles obtained by varying parameters in fully dynamic models, usually in two dimensions, and qualitatively comparing results to independent tomographic models. This approach is powerful to identify the effect of the viscosity structure (Čížková and Bina, 2019), rheology (Garel et al., 2014), and phase changes (Agrusta et al., 2017) on deep slab dip angle, however, it is not as direct to compare results to constraints. However, two-dimensional or three-dimensional regional models do not capture the effect large-scale mantle flow on the location and dip angle of slabs (Peng and Liu, 2023). Predicting the evolution of deep slab dip angles in fully dynamic global models requires resolutions of the order of one kilometre and large lateral viscosity contrasts (six order of magnitude or more; Stadler et al., 2010; Coltice et al., 2019), both of which remain computationally challenging in global mantle flow models and have only been achieved using adaptive mesh refinement in models of present-day mantle flow (Stadler et al., 2010). Lower resolution models with large lateral viscosity contrasts predict one-sided subduction zones alongside continents, but two-sided intra-oceanic subduction zones (Coltice et al., 2019).

4.2.2. Tomographic models and vote maps

The interaction between slabs and the transition zone leads to interesting geodynamic questions related to contrasted deep slab dip angles (e.g., Garel et al., 2014; Goes et al., 2017; Čížková and Bina, 2019) which motivated this study. While vote maps of global tomographic models reveal fast-velocity anomalies that we interpreted as slabs (e.g., Fig. 4), this mapping is limited because global tomographic models poorly constrain the structure of the mantle between ~400 km and 1000 km depth, although this can be improved by including surface wave overtones (Ritsema et al., 2004). We primarily focused on P-wave tomographic models because these better resolve slabs beneath dense seismic networks (Supplementary Figure 1), although S-wave tomographic models achieve a better global coverage (Supplementary Figure 2) (Grand, 2002; Ritsema et al., 2004). We assumed that positive seismic velocity anomalies represent cold mantle and therefore slabs, and we did not consider the influence of chemical variations that may be significant in the lower 1000 km of the mantle (Trampert et al., 2004).

The selection of tomographic models from which to derive vote maps influences the result. Here we selected a large number of global tomographic models following early work with vote maps (Shephard et al., 2017; Coltice and Shephard, 2018) and to capture information from as many tomographic models as possible. We note that our selection of tomographic models includes three DETOX models from Hosseini et al. (2020), which results in an over-representation of the features common to these three similar global tomographic models. An alternative approach would consist of selecting a subset of tomographic models representative of the data types and processing techniques used in tomographic inversions (Shephard et al., 2021). Investigating the match between individual tomographic models and mantle flow models is also tractable when fewer tomographic models are considered (e.g., Peng and Liu,

2023) or when the data are reduced using spherical harmonics correlations (Becker and Boschi, 2002) or cluster analysis (Flament et al., 2022).

4.2.3. Inferring the location of past subduction zones from tomographic models

While mantle flow models predict subducted slabs, a complementary approach consists of mapping slabs in tomographic models, and matching them with geological evidence of past subduction at Earth's surface to infer the past location of subduction zones (Wu et al., 2016; Zahirovic et al., 2016; Van der Meer et al., 2018); this approach requires selecting a threshold to map slabs from tomography, inferring a sinking rate, and assuming that slabs sink vertically. Some limits to the approach are that slab sinking rates depend on depth because slabs slow down as they approach the core-mantle boundary (Flament, 2019; Peng and Liu, 2022) and that large-scale mantle flow may cause slabs to be advected laterally (Peng et al., 2021), which is inconsistent with the assumption of vertically sinking slabs. The approach is also limited to inferring past subduction zones from ~150 Ma and perhaps up to ~250 Ma depending on slab sinking rates (Van der Meer et al., 2018; Flament, 2019). We note that this approach has been used to infer the past location of subduction zones in some regions in the global tectonic reconstructions that we use (e.g., Zahirovic et al., 2016). In this respect, our reconstructions of past mantle flow are not entirely independent from tomographic models.

4.2.3. Comparing slabs in global mantle flow and global tomographic models

Comparisons between mantle flow and tomographic models have been carried out in previous work (Bunge et al., 1998; Becker and Boschi, 2002), usually to derive global correlations for both slow and fast structures. We map and quantify the spatial match between mantle slabs and tomographic models down to 1,000 km depth, which complements previous work that focused on the lower mantle (Flament, 2019) or on fewer tomographic models

(Shephard et al., 2012; Peng and Liu, 2023). Quantifying and visualising the match between slabs predicted by reconstructions of past mantle flow models and tomographic models makes it possible to identify areas where the models do not match tomographic models, so that tectonic reconstructions can be improved. This comparison (Fig. 6) suggests that global reference frames and the subduction history under north America (Liu et al., 2008), southern South America (Faccenna et al., 2017; Chen et al., 2019), between India and Asia (Zahirovic et al., 2012; Jagoutz et al., 2015) and under Japan (Domeier et al., 2017; Wu et al., 2022) may need to be refined in global tectonic reconstructions. In some locations, the timing or location of subduction zones is likely to be off in current global tectonic reconstructions. Improving tectonic reconstructions based on the match between mantle flow and tomographic models is complex and uncertain because the location of predicted slabs depends on the reference frame (Shephard et al., 2012) and on large-scale flow (Peng and Liu, 2023) which is determined by the assumptions and parameters of the flow model. Nevertheless, some first-order mismatches are intriguing. For example, global reconstructions show continuous subduction along South America for the last 500 Myr (Merdith et al., 2021), however, tomographic models suggest that subduction may have initiated around 50 Ma south of 38ºS (Faccenna et al., 2017; Chen et al., 2019). This problem requires further work, even though the resolution of tomographic models is limited in the southern hemisphere (Romanowicz, 2008).

The approach we used to assess the success of mantle flow models in matching slabs inferred from vote maps of tomographic model requires a strict match in the location of the predicted and inferred structure. This strict approach results in an overall relatively low sensitivity score (Fig. 7) because the target area is small (Fig. 1) and close matches (Fig. 6) are not considered. The approach could be improved to consider close matches for example by ‘stretching’ the models (Becker and Boschi, 2002) or by using an object-based approach as is done in weather forecasting (Davis et al., 2009). Another possible refinement of our method would involve converting the predictions of our mantle flow models to seismic velocities and filtering the results using a resolution operator (Schuberth et al., 2009; Shephard et al., 2012), however, this would limit the comparison to tomographic models for which the resolution operator is publicly available (Ritsema et al., 1999; Shephard et al., 2012).

4. Conclusion

We analysed the deep slab dip angles in paleo-geographically constrained mantle flow models, and found that these models reproduce the first-order characteristics of penetrating slabs (such as the Mariana Trench) and stagnating slabs (such as the Pacific slab to the north of the Japanese Islands). Our results confirm that a key factor controlling deep slab dip angle is the mobility of trenches, with stable trenches leading to slabs that penetrate into the lower mantle, while retreating trenches can lead to slabs stagnating on top of the lower mantle. We found that slabs can stagnate in the upper mantle if there is a viscosity contrast between the upper mantle and the lower mantle, which is consistent with previous work. An increase in viscosity by a factor of ten was sufficient to obtain slab stagnation in the considered models. Our results suggest that deep slab dip angle can be used to calibrate the viscosity contrast between the upper and lower mantle as well as the range of values for the Rayleigh number of mantle flow models, because a small Rayleigh number (8.60×10^6) leads to stagnating slabs globally, and a large Rayleigh number (8.60×10^9) leads to penetrating slabs globally. A Rayleigh number equal to 8.60×10^8 was found to be appropriate for the considered models. Our global models complement independent regional approaches and make it possible to identify regions in which tectonic reconstructions should be revisited. For example, we suggest that the retreat of the Pacific slab to the north of the Japanese Island could occur over a larger distance and a longer period than in the reconstructions used in this work, and that the subduction history along South America should be revisited before ~50 Ma and south of ~38ºS.

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6. Author contributions (CRediT author statement)

Joshua Weber: Formal Analysis, Investigation, Validation, Writing – Original Draft, Visualization. **Nicolas Flament:** Conceptualization, Methodology, Validation, Writing – Review & Editing, Visualization, Resources, Supervision, Project Administration, Funding Acquisition.

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