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Abstract: Convection modelling with realistic plate histories has been limited by the availability of published gridded kinematic models. While alternative kinematic models may exist for a given region, they are not easily converted into gridded velocity models, because of the difficulty in compiling closed time-dependent plate polygons consistent with a particular plate rotation history. This problem arises because even though the location of mid-ocean ridges through time is usually well constrained, the location of subduction trenches is not always well known for the geological past. In addition, while a rigid plate may be defined as a continuous body, any two points of which have no motion relative to each other, the boundaries of plates continuously evolve. If regional plate boundaries can easily be calculated and defined over a series of time steps in a self-consistent manner, then compiling time-dependent velocity and oceanic palaeo age-grids is greatly simplified from a given plate kinematic model as input for mantle convection modelling. We present a solution to this problem, implemented through user-friendly open source software, and provide a use-case

R. Stephenson
Editor-in-Chief
Journal of Geodynamics

Dear Dr. Stephenson,

I present to you an article for your consideration to publish as a relevant, novel and interesting piece of geoscientific research. The article is entitled "Convection Models with Imposed Plate Motion and Thermal Histories".

The article connects two broad fields of interest to your readers: Mantle convection and plate kinematics. Connections between these fields have been made in the past, but these have lacked the methodology in workflow, the detail attainable (provided as a sample in a case study) and therefore the ability to tightly constrain convection models with tectonic and seismic observations. This research is original and not consideration for publication anywhere else and was conducted as part of a PhD undertaken at the University of Sydney by myself, the corresponding author.

In your correspondence regarding this article, please direct it to:

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I am currently employed as a post doc at Simula Research Laboratory Martin Linges v 17, Fornebu, N-1325, Lysaker, Norway, but work remotely from the address given above. This is likely to be the case for the time that the article is under consideration, but I will notify you of any changes.

As for possible reviewers I could suggest the following: Hans-Peter Bunge, Saskia Goes, Wouter Schellart, Carolina Lithgow-Bertelloni.

Yours sincerely,

Stuart Clark

Convection Models with Imposed Plate Motion and Thermal Histories

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Abstract

Convection modelling with realistic plate histories has been limited by the availability of published gridded kinematic models. While alternative kinematic models may exist for a given region, they are not easily converted into gridded velocity models, because of the difficulty in compiling closed time-dependent plate polygons consistent with a particular plate rotation history. This problem arises because even though the location of mid-ocean ridges through time is usually well constrained, the location of subduction trenches is not always well known for the geological past. In addition, while a rigid plate may be defined as a continuous body, any two points of which have no motion relative to each other, the boundaries of plates continuously evolve. If regional plate boundaries can easily be calculated and defined over a series of time steps in a self-consistent manner, then compiling time-dependent velocity and oceanic palaeo age-grids is greatly simplified from a given plate kinematic model as input for mantle convection modelling. We present a solution to this problem, implemented through user-friendly open source software, and provide a use-case example for the Kamchatka region by combining palaeo-plate velocity and oceanic palaeo-age-grids with a convection model for the Late Cretaceous/Tertiary. Our combined kinematic-mantle convection model is validated by comparison with upper mantle tomography.

Keywords: Plate kinematics; mantle convection; Kamchatka; Aleutian Basin; Shirshov Ridge

Introduction

Developing kinematic models involving the subduction of ocean crust from the Cretaceous to the present is based on combining relative and absolute plate motion models (O'Neill et al., 2005) and by reconstructing now subducted portions of plates based on marine geophysical data and the rules of plate tectonics. Fracture zones and magnetic lineations show the direction and speed of spreading, respectively. As the history of an oceanic portion of a plate is determined, so are the continental blocks and other less transient features that are fixed to them.

To test different kinematic models using mantle convection models, a self-consistent time-dependent set of plate boundaries is required. Here consistency means the degree to which the plate boundaries move with the rotation model for each plate. For subduction trenches, the plate boundary should be fixed to the overriding plate and not digitised independently for each time step, as is often the case.

Little progress has been made to present geological reconstructions as a consistent sets of plate boundaries and rotations since Lithgow-Bertelloni and Richards (1998) developed their global models. As they have outlined, gathering the information to make a consistent reconstruction is no easy task. Some authors may offer a reconstruction, but without rotations to describe the movement of the plate boundaries. Reconstructions based on geochemical or geological data generally lack the required detail for plate boundaries to be reconstructed on a per million-year basis.

Gurnis and Müller (2003) presented velocity grids for the Australian region but there have been no other regional velocity grids published since. Gurnis and Müller’s (2003) methodology for producing these grids is not entirely self-consistent, as portions of their plate boundaries move with respect to the overriding plate. This reflects a lack of software and workflows to construct time-dependent plate velocity grids.

Lithgow-Bertelloni and Richards' (1998) model is useful for low-resolution global convection modelling, but it lacks accuracy for regional modelling. Their model includes only seventeen plates globally for the present day, while the plate boundaries are extremely low in resolution.

Richards et. al. (Richards et al., 2000) suggest that to improve the general mantle circulation model, uncertainties in plate reconstructions and a better treatment of rheology, among other things, are required. While the resultant uncertainties in the mantle circulation model would be difficult to derive from uncertainties in plate reconstructions, this paper presents a method of easily calculating kinematic inputs from plate reconstructions such that different reconstructions can be tested in a given region.

A plate reconstruction model has been developed for the Kamchatka region (**Figure 1**) to illustrate the methodology of imposing plate histories on mantle convection models. This region has been chosen because the complexity and variance of reconstructions for the region illustrates the usefulness of using interactive software designed to generate self-consistent kinematic models to discern between alternative tectonic reconstructions. There are a number of tectonic reconstructions published for the Kamchatka region (Baranov et al., 1991; Gaedicke et al., 2000; Geist and Scholl, 1994; Konstantinovskaia, 2000; Park et al., 2002; Scholl et al., 1987; Seliverstov, 1997) but they are diagrammatic and are not published with rotations. These reconstructions have been examined in detail and a simplified kinematic model with reconstructions has been generated for Kamchatka.

Methodology

Constructing Consistent Plate Boundaries

In regional modelling, each plate is composed of a number of boundaries, some of which are the edges of the regional box. Those that are not edge boundaries are assigned a rotation based on the type of boundary it represents and the plates to either side. For subduction boundaries, the boundary is rotated according to which plate is the overriding plate. For spreading centres, the boundary is given a rotation that is half the motion between the plates, neglecting asymmetric spreading. For transform faults, the rotation given can match the motion of either plate, unless the transform is fairly oblique, in which case the overriding plate should be selected.

In the user-friendly interactive program that we have written called Kinematica, plate boundaries can be digitised so as to allow the user to construct plate polygons (**Figure 2**). These plate boundaries can then be assigned properties by clicking on the desired feature and clicking *Edit->Line Properties*. A comprehensive list of properties can be assigned to allow for outputting features in the PLATES© (Royer et al., 1992) format.

The Kamchatka Peninsula and its Tectonic Setting

The Kamchatka Peninsula

The Kamchatka peninsula is part of the overriding plate large Kuril-Kamchatka subduction trench which spans the region from just North of Japan to where the Aleutian Arc meets the Kamchatka peninsula. The Kamchatka Peninsula is made up of terranes that have been accreted on the eastern side of Eurasia since the Mesozoic (Park et al., 2002). The Pacific plate is subducting at approximately a rate of 7cm/yr in this region (Tsvetkov, 1991), trench perpendicular under the peninsula. There is strike-slip motion between the Aleutian Arc and the Pacific plate, as the

Arc subducts more slowly (Gaedicke et al., 2000). To the west of the peninsula lies the Sea of Okhtosk

The Emperor Sea mount chain is being subducted beneath the Kamchatka peninsula just south of the intersection point of the Aleutian Arc with Kamchatka (Churikova et al., 2001). The junction is also interesting because its landward continuation delineates the northernmost point of active volcanism (Churikova et al., 2001) where there are three separate Quaternary volcanic arcs, unique to this region (Tatsumi et al., 1995).

The Aleutian Arc

The Aleutian Arc provides a distinct boundary between the Bering Sea and the Pacific Ocean. The Pacific plate moves near parallel to the Arc at its westernmost end, where it intersects the Kamchatka peninsula. Further to the East, the Pacific plate subducts underneath the Arc, creating a tear in the subducting plate (Yogodzinski et al., 2001). The Aleutian Arc is moving relative to the Kamchatka peninsula, and there is evidence that the Kamchatka Cape (Geist and Scholl, 1994) was previously part of the Aleutian Arc and had collided with the Kamchatka peninsula. Since the middle Eocene the Aleutian Arc has been extending parallel to the arc induced by trench parallel motion of the Pacific plate, especially in the Western Aleutian Islands (Lallemant and Oldow, 2000). Such an extension does not broadly change the shape of the arc. Therefore, for purposes of this reconstruction, the position of the arc will be fixed to the North-American plate, neglecting the extensional component.

The Komandorsky and Aleutian Basins

The Komandorsky Basin is bordered by the Shirshov ridge to the East, the Kamchatka Peninsula in the North-West and the Aleutian Arc in the South. The Shirshov Ridge is a submerged island arc (Baranov et al., 1991).

There was active spreading in the Komandorsky Basin between 40 And 10 Myr ago (Gaedicke et al., 2000) and volcanism in the Sdrenny Range (Park et al., 2002) provides evidence for subduction of the basin underneath Northern Kamchatka. Magnetic lineations exist in the basin, but they are difficult to date (Konstantinovskaia, 2000). There are four major NE trending fracture zones in the basin, which give the direction of spreading. There is conflict over whether the spreading centre is currently centred on the basin (Konstantinovskaia, 2000) or is mainly subducted except in the south of the basin (Baranov et al., 1991).

The present day location of the Shirshov ridge is the easternmost limit of the Komandorsky basin. For times older than 45 Ma and younger than 10 Ma, the Shirshov ridge has been fixed to the Kamchatka peninsula. At times younger than 45 Ma, the direction of motion of the plate was determined so as to be parallel with the Aleutian Arc and Pacific plate motion at the junction of Kamchatka with the Aleutian Arc. This motion is also in agreement with the strike of the major fracture zones in the Komandorsky Basin (Baranov et al., 1991). Using a plate velocity suggested by Park (2002) a complete reconstruction of the plate was possible, suggesting that the Shirshov ridge formed as a subduction related arc as Aleutian Basin subduction initiated underneath the Komandorsky. Prior to this the Pacific-Aleutian Basin motion would suggest that the eastern plate boundary of the Komandorsky Basin was a transform fault.

Baranov (1991) presents the Shirshov ridge as originating as part of the Aleutian Arc, while other authors suggest that it originates as the forearc from broadly north-south trending subduction trench (Lizarralde et al., 2002; Tsvetkov, 1991). We implement this latter model of Lizarralde (2002) in particular for

The largest basin in the region studied is the Aleutian Basin. The Aleutian Basin is found to the east of the Komandorsky Basin and bounded by the Beringian Rise to the west and the Aleutian Arc to the south. The Aleutian

Basin is likely to be a remnant fragment of the Kula plate of Cretaceous age (Kepezhinskas et al., 1993) that separated when subduction jumped southward from the Beringian Margin to the Aleutian Arc at about 50-45 Ma (Lizarralde et al., 2002).

The Pacific and Kula plates

Engebretson and Cox (1984) suggested that during the Paleocene and Early Eocene, the Kula plate was subducting underneath Alaska and the Beringian Margin, while the Pacific plate was subducting underneath the Kamchatka peninsula. Active spreading between the Kula and Pacific plates stopped in the middle Eocene and the Kula plate finally disappeared beneath the Aleutian Arc, along with the Kula-Pacific spreading centre (Gorbatov et al., 2000), except for possible remnants left in the Western Philippines (Lewis et al., 2002) and the Aleutian Basin (Fliedner and Klemperer, 2000; Lizarralde et al., 2002).

The Eurasian and North American Plates

There was significant uncertainty as to whether Kamchatka is part of a microplate whose western boundary is somewhere in the Okhtosk Sea or where it is fixed to North America and the Eurasian/North American plate boundary extends through Siberia and meets the Kuril trench just North of Japan (Geist and Scholl, 1994). This is because the plate boundary location between the North American plate and the Eurasian plate was not well constrained until Steblov (2003) produced definite GPS evidence that the region east of the Cherskiy range, Siberia, is part of the North American plate. It follows that for the purpose of our reconstructions the Eurasian Plate is not relevant because it is outside of our model region.

Forming Plate Polygons

Finite plate rotations were generated using constraints from the tectonic history above to derive a kinematic model for the Kamchatka region since 70 Ma. After digitising a sufficient number of plate boundaries using Kinematica, the user can begin plate polygon closure. All tectonic features of interest are rotated in a chosen absolute reference frame and to a desired time for polygon reconstruction. The user starts the *Polygon Formation Tool* and can then select lines to form the polygon. Two lines need not intersect, but if they do not, the midpoint of the two nearest ends will be chosen. If a regional boundary cuts through a plate, then the regional boundary should be selected as part of the plate polygon by clicking *N, S, E* or *W* as appropriate. Once a circuit has been completed, the user can then select *Create Polygon* and the new polygon will be shown in a thicker line (**Figure 3**). Finally, this will need to be repeated so that the plate polygons cover the entire region.

Plate boundaries can then be rotated to a chosen time of reconstruction, and a new polygon created for that time. Polygons are only valid for a single time-step, so the previously created polygons will vanish when lines are reconstructed to a different age, only to reappear when returning to that reconstruction.

Closed polygons can then be used to prepare boundary conditions for mantle convection models by masking gridded data for the area by the plate polygons. Two boundary conditions – namely lithospheric temperature and velocity – are the most important for tying mantle convection models to plate motions.

Temperature Boundary Condition

Oceanic paleoage grids are constructed as described by Müller et. al. (2006) for the region of interest. Ages are then superimposed on the convection model by calculating the temperature T_d at each given depth, d (in meters) via the cooling half-space model (Parker and Oldenburg, 1973):

$$T_d = T_m erf\left(\frac{d}{2\sqrt{\kappa t}}\right) \qquad (1)$$

Where T_m is the ambient mantle temperature, t is the age of the crust in seconds. For the initial time step, the temperature profile is applied through the entire depth of the model. At later times, the temperature from the age-grid is imposed on the model by a linearly decreasing proportion from one hundred percent at 0km depth to fifty percent at 30km depth. The ambient temperature proportion increases correspondingly from the surface where it is zero percent to fifty percent at 30km depth. At temperatures greater that thirty kilometers, the ambient temperature is used only.

Simulating Subduction with an Overriding Plate

Real-earth subduction is an asymmetric process (Müller et al., 1998); on one side of the trench the plate is pushed and pulled into the mantle, whilst on the other side, the over-riding plate does not descend into the mantle, although it greatly affected by subduction related processes such as through volcanism and dynamic topography.

In order to replicate this asymmetry, it is not enough simply to push one plate into the other. Pushing the subducting plate into the overriding plate will couple the slab viscously to the overriding plate, forcing it down into the mantle. This in turn slows and flattens subduction in every instance, and the plate sinks symmetrically.

To solve this problem in two-dimensional models, Davies (1999) imposes a negative velocity at the surface in the region immediately behind the trench. The amplitude of the velocity is commensurate with that of the plate, with an opposite direction. The effect is to introduce counter flow of the upper mantle material, thinning the overriding plate in the region and creating a high temperature and thus low viscosity zone above the subducting slab. This rapid counter flow has been modelled in two-dimensional thermal models (Keleman et al., 2003).

As the slab subducts, water in subducting marine sediments percolates into the mantle, reducing its melting temperature. This water is then released from the sediments when the slab reaches a certain pressure and temperature, between approximately 30km and 100km depth (Keleman et al., 2003). As the slab descends, the water boils off the slab and into the mantle immediately above the slab, lowering its viscosity and creating the mantle-wedge (Billen et al., 2003; Carlson and Miller, 2003; Keken, 2003; Keleman et al., 2003).. To simulate this lowering of viscosity, the temperature of the region immediately behind the trench has been imposed to match that of the mantle below 1 million-year old crust.

Imposing velocity conditions in three-dimensions is not a trivial matter. It is simplest to impose a high-temperature, low-viscosity wedge directly. In three-dimensional models with imposed histories of plate velocities and ages, a solution is to construct a warm back-arc region in-front of the subducting slab that replicates the thinning and decoupling achieved by the opposing velocities used by Davies (1999). The region to be defined can be taken from the trench position with a width of about 400 km (orthogonal to the trench) and a depth to the upper surface of the slab.

While more complicated treatments of the mantle wedge have been attempted (Manea and Gurnis, 2006), this is not the focus of this paper.

We have implemented a relatively simple solution which overcomes the viscous-coupling of the down-going slab to the overriding plate without parameterising such things as the water-content in the mantle wedge and temperature and pressure conditions for partial melting.

The effect of not including this high temperature and hence low-viscosity zone above the slab is shown in **Figure 4(a)**, where the subducting plate drags with it the base of the overriding plate, adding additional cold material to the mantle. **Figure 4(b)** shows the difference if a mantle wedge region is included. Importantly there is a gap between the down-going slab and the base of the overriding plate preventing viscous coupling from occurring.

Mantle Convection, Generated Inputs

Model Mesh

To properly resolve the sharp contrast between the surface slab and the mantle immediately beneath, it is important to generate a grid with refinement in the radial direction. To achieve this, the element thickness is linearly scaled from a resolution of 10km at the surface to 40 km below the mantle transition zone at 1000km depth.

The geographic grid at the surface is given in degrees, corresponding to about 48km in longitude and latitudinally increasing from 12km in the South to 7.25 km in the North.

Velocity Grid

With the closed plate polygons obtained using the methodology above, the velocity field is relatively straightforward to calculate. For each reconstruction age, a stage rotation is calculated for every plate in 0.5 million-year intervals. A routine to determine if a point is inside a polygon is then applied and the point is rotated to a new location given the appropriate rotation for that plate. The average speed is then found from the distance between the points, and the direction is given by the azimuth from one to the other on a sphere.

Age Grid

As mentioned above, the imposed surface boundary condition is derived from a set of oceanic palaeo-age-grids. However, the age-grids are modified in certain areas by assigning particular ages to the points that either fall within the low-viscosity zone or where magnetic anomalies are absent. The low viscosity mantle wedge region can be seen as a zone of relatively young (1 Ma) imposed oceanic age parallel to the Kamchatka trench in **Figure**. In the absence of magnetic anomaly constraints on the ages of the ocean basins in the Bering Sea, the Komandorsky Basin and the Aleutian Basin have been assigned an age of twenty million years (**Figure 5**), an upper limit on their age (Gaedicke et al., 2000).

Mantle Convection model, brief description

The convection model used is a finite element solver, CitcomS (Tan et al., 2006) (Zhong et al., 2000), with temperature-dependent viscosity and incompressibility and the equations are solved in spherical coordinates. The sides and the bottom of the annular prism are no-slip, while the surface has an imposed velocity from the velocity grids mentioned above. **Table 1** lists the reference values for the model.

To prevent the upwelling or down-welling of material at the boundaries of the box, a zone, 30km wide and 40km deep from the edge has been added in which temperatures are overwritten with the default temperatures supplied by the age-grid.

The mantle is layered vertically with a step function, the viscosity at each point calculated according to the temperature at that point, T, according to the formula:

$$\eta = \eta_o^l e^{\left(\frac{E_a}{RT}\right)}$$

When η_o^l is the reference viscosity for each layer, respectively 4x10^{21} $kgm^{-1}s^{-1}$ for the lithosphere, 4x10^{19} $kgm^{-1}s^{-1}$ for the asthenosphere, 4x10^{21} $kgm^{-1}s^{-1}$ for the upper mantle and 4x10^{22} $kgm^{-1}s^{-1}$ for the lower mantle. E_a is the activation energy, 300 $kJmol^{-1}$, R is the gas constant, 8.3144 $JK^{-1}mol^{-1}$. To limit the variation of viscosity between the layers so that the model is properly resolved, the viscosity is capped at 4x10^{23} $kgm^{-1}s^{-1}$ and has a minimum of 4x10^{19} $kgm^{-1}s^{-1}$. The resultant viscosity initial position is show in **Figure 6**, closely replicating the viscosity layering of Moresi and Gurnis (1996).

Results

Using Kinematica, a set of plate boundaries were created for the period 70 Ma to the present in one million year intervals. These plate boundaries covered the Kamchatka region, from 130^{o}E to 160^{o}W and from 45^{o}N to 65^{o}N. These plate boundaries were then used to make a set of paleo-plate velocity and oceanic paleo-age-grids at 1 m.y. intervals.

Figure5 shows the generated plate polygons for the Pacific/Kula, Kamchatka peninsula, North-America and the Komandorsky and Aleutian Basins with the generated age-grid input. Overlain are selected velocity vectors from the velocity grid. The age-grid for the Aleutian Basin was synthesised as it was a piece of the Kula plate that was separated following the Pacific plate change in motion at 50 Ma (see above for the discussion). Thus the Aleutian Basin was given an age based on the age of the Kula plate before 50 Ma (**Figure5 (c)**). The Komandorsky basin was assigned a mean age of 10 Ma until spreading in the Komandorsky basin ceased at 9 Ma, at which case the basin aged normally (**Figure 5**).

The Pacific-Kula mid-ocean ridge is close to the trench at 70 Ma, the beginning of the model and the ocean-floor ages are consequently young. After the ridge is subducted, no new ocean floor is created in this region and the ocean floor ages get progressively older, until the present when they represent some of the oldest ocean floor in the world, at 120 Myr.

Comparison with Tomography

Tomography can provide an important constraint for plate kinematic models, giving the location of both temperature and geochemical anomalies. In **Figure 7**, the models of Ritsema and van Heijst (2002)'s shear wave velocity anomalies are plotted as seismic velocity variations, with contours of the subducting slab from the convection models overlain, at two different depths. The first figure is at 430km near the top of the transition zone, while the second is at 650km, near the bottom. The slabs are much wider in **Figure 7(b)** because they are being spread out at the base of the transition zone, unable to puncture it within the time frame of the model (70 Ma). In **Figure7(a)**, slab material is found underneath the present day Aleutian basin where there is a seismic fast anomaly of ~ 1% (Ritsema and van Heijst, 2002).

Slab material is also found along the Kuril-Kamchatka arc region where there are even stronger anomalies in the order of 2%, especially in the south. Finally a subducted slab, which is a product of Komandorsky Basin subduction, can be seen between 150ºE and 155ºE and 60ºN and 63ºN. In **Figure 7(b)**, under the Aleutian Basin, the relatively cold slab material has not yet reached the bottom of the transition zone suggesting that the kinematic model did not encompass a wide enough area – slab material from Pacific-East Aleutian Arc subduction has not significantly entered into the mantle as material is prevented from subducting close to the eastern model region boundary to remove edge effects. The subduction models show good first order agreement with seismic tomography images, with the location of slabs in the mantle corresponding to fast anomalies in the tomography model.

Discussion

The lack of tools to create plate polygons has been a major obstacle in connecting mantle convection codes with data of plate kinematic and thermal histories. While seismic tomography has been used as an initial condition in models with time reversed (with the diffusion component of the energy equation removed) to generate a mantle temperature volume as a starting point for a forward model, this has limited applicability to subduction models. With time reversed, cold material will simply rise directly upward from the initial position set by the tomography. Current time-reversal techniques cannot take into consideration slab dip and deflection of the slab as it hits the 670km transition zone. Although this model starts with a mantle free of cold subduction-related remnants, the models are started early enough to generate slab material in the transition zone. Slab material below this point, from an early phase of subduction, is less relevant to surface processes.

On the other hand, kinematic models that are developed from regional geological data, well-data, magnetic lineations, petrology and other sources are difficult to test against a common standard. Kinematic models developed from such data are often sketches, whose plate boundaries are not rotated, and the location of the trench through time is usually not placed consistently with the reconstruction for the overriding plate. Consistency of the overriding plate and trench location is a vital condition of generating subduction in the convection model.

Conclusions

The interactive software Kinematica facilitates the digitisation and time evolution of plate boundaries consistent with a given plate rotation hierarchy underlying a kinematic model. Using the Kamchatka region as a test-case, we have shown that these plate boundaries can then be used to create surface boundary conditions for convection models. Outputs of the models can then be tested against observations, validating a particular plate-kinematic model. Although mantle tomography was used here to test the kinematic model, other forms of data can also be used, depending on availability and the mantle convection code used. For example, vertical stress can be compared against a subsidence history for a given region. We have tested the origin of the Komandorsky Basin, the Shirshov ridge and the Aleutian Basin by implementing the model of Lizarralde et al. (2002) and have validated it against published seismic tomography (Ritsema and van Heijst, 2002). The combined plate tectonic/mantle convection model is consistent with the locations of fast shear-wave anomalies in the upper mantle.

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Table 1: Variables for the Mantle Convection Code

Variable Name	Value
Reference Density, $\boldsymbol{\rho_o}$	3500 kg/m^3
Temperature Contrast, β	1400 K
Thermal Diffusivity, κ	1×10^{-6} m^2/s
Coefficient of Thermal Expansion, α	2×10^{-5} K^{-1}
Reference Depth, ***d***	6371 km
Reference viscosity, $\boldsymbol{\eta_o}$	4×10^{21} kg /ms
Gravitational Acceleration, **g**	10m/s^2
Rayleigh Number, $\boldsymbol{R_a}$	7.1×10^7

List of Figures

Figure 1. Topography and bathymetry of the Kamchatka region in meters with the following labels: AA - Aleutian Arc, AB - Aleutian Basin, AT - Aleutian Trench, BR - Bowers Ridge, EC - Emperor Sea Mount Chain, KB - Komandorsky Basin, KKT - Kuril-Kamchatka Trench, KP - Kamchatka Peninsula, SO - Sea of Okhotsk. The Kuril-Kamchatka Trench and Aluetian Trench demarcate the northern boundary of the Pacific plate in this region. The other features shown are on the North American plate.

Figure 2. Digitising the Kuril-Kamchatka trench.

Figure 3. Kinematica: the user digitises plate boundaries continuing their strike beyond their end so as to ensure and intersection point even after the plate boundaries are rotated. The plate polygon tool (showing each line - SKP - Shirshov/Komandorsky plate, KAM - Kuril-Kamchatka, PAC - Pacific plate boundary (Aleutian arc). After clicking "Create Polygon" the Komandorsky basin is shown (in bold) as a plate polygon.

Figure 4. Temperature and velocity for a 2-1/2 dimensional time evolved model (to ~ 25 Ma) with a small mantle wedge region. Temperature scale shown is dimensionless, but can easily be scaled by multiplying by 1400ºC. The slab is pushed at 7 cm/yr and couples viscously with the overriding plate. **(a)** The small (~25 km) gap of hot (1400ºC) material is not sufficient to decouple the subducting plate from the overriding and the overriding plate is dragged into the mantle with the subducting plate **(b)** The larger gap (125km) of hot (1400ºC) material now decouples the subducting plate from the overriding.

Figure 5. (a)-(h): Oceanic Paleo-age with velocity grids for 70 Ma to the present as labelled.

Figure 6. Temperature and log (viscosity) profile shown for a lithospheric age of 50 Ma. Although the viscosity profile shows viscosities higher than 4x1023, this number represents the numerical cap imposed.

Figure 7. Seismic shear wave velocity anomalies from the Ritsema and van Heijst (2002) at **(a)** 430km and **(b)** 650km depth with slab temperature contour overlain. The contour represents 1330ºC while the present day coastline is in purple.

Figure 1
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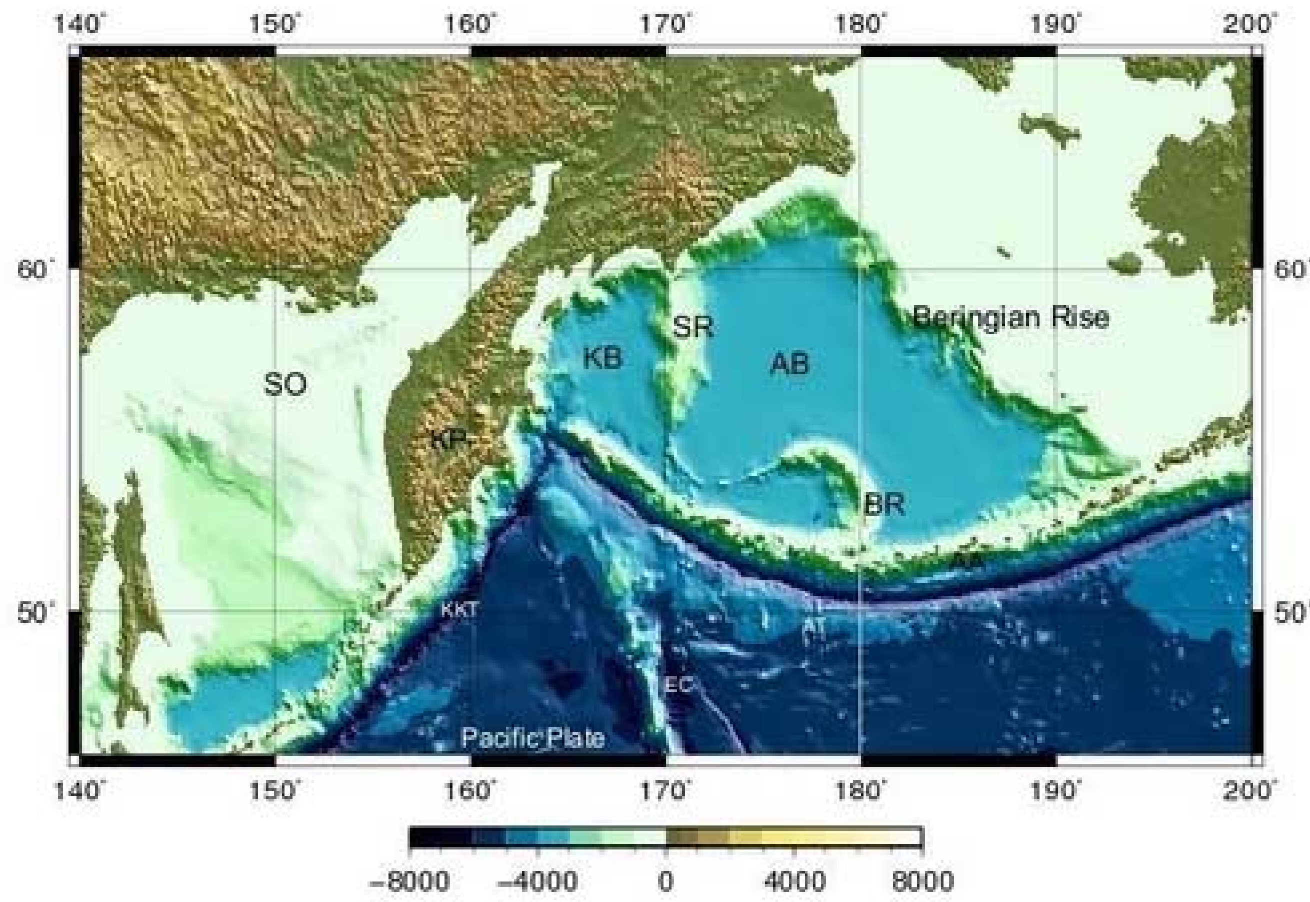

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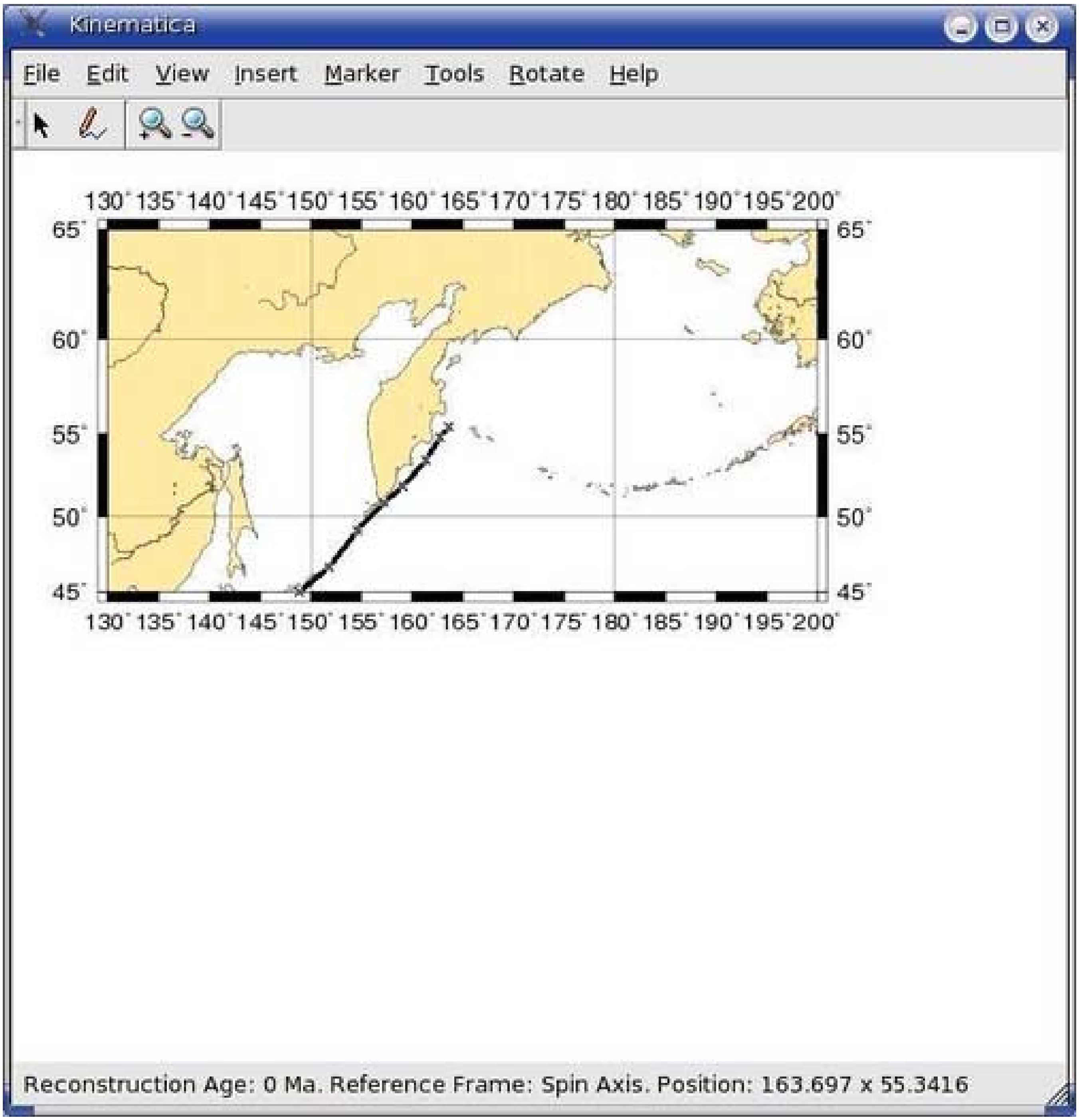

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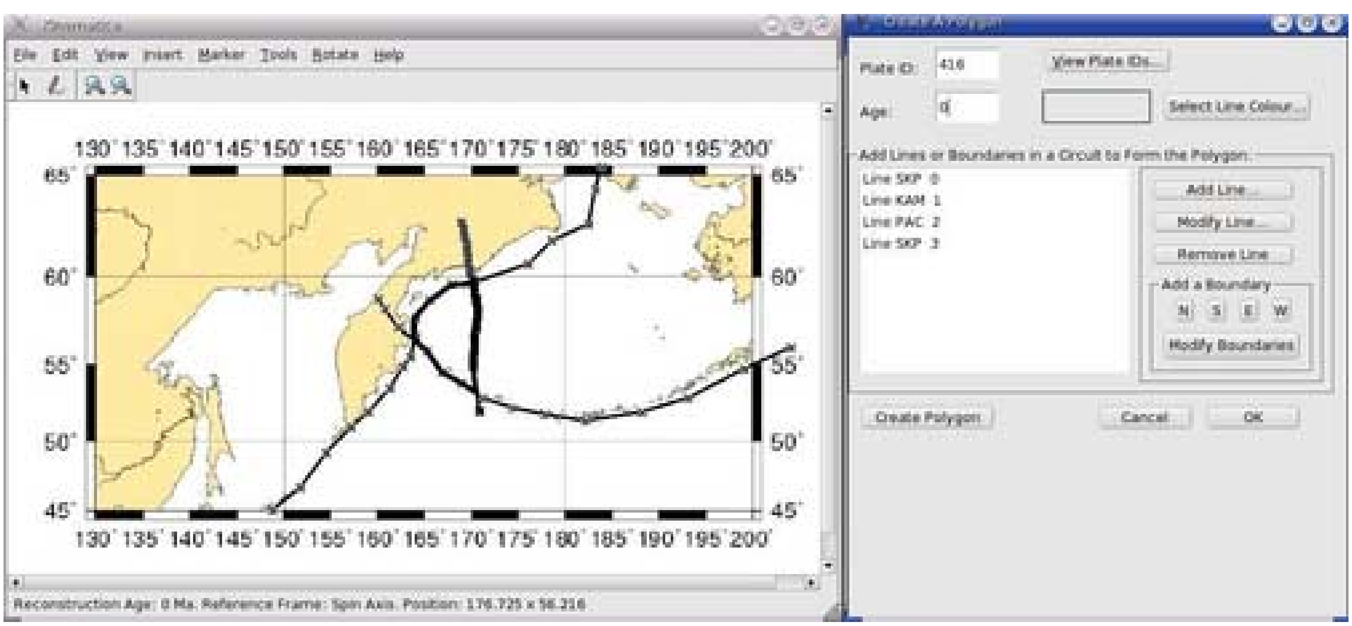

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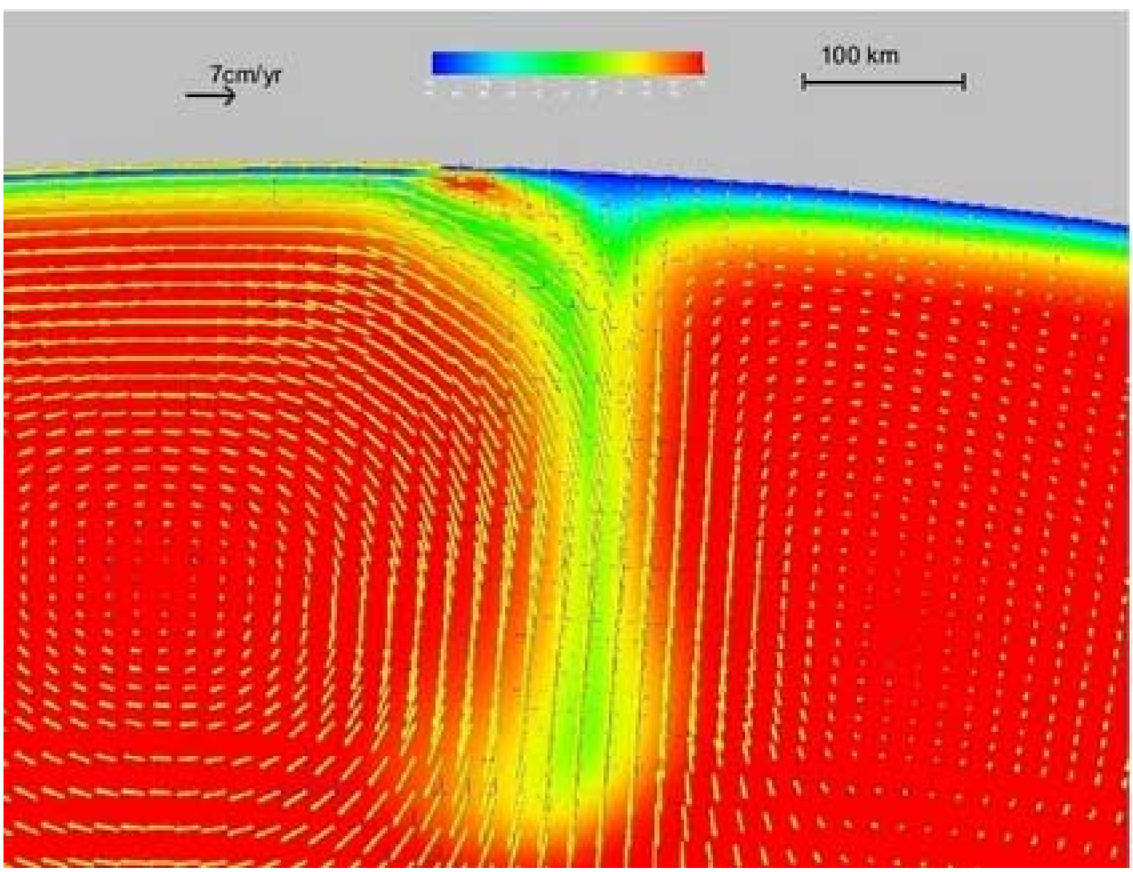

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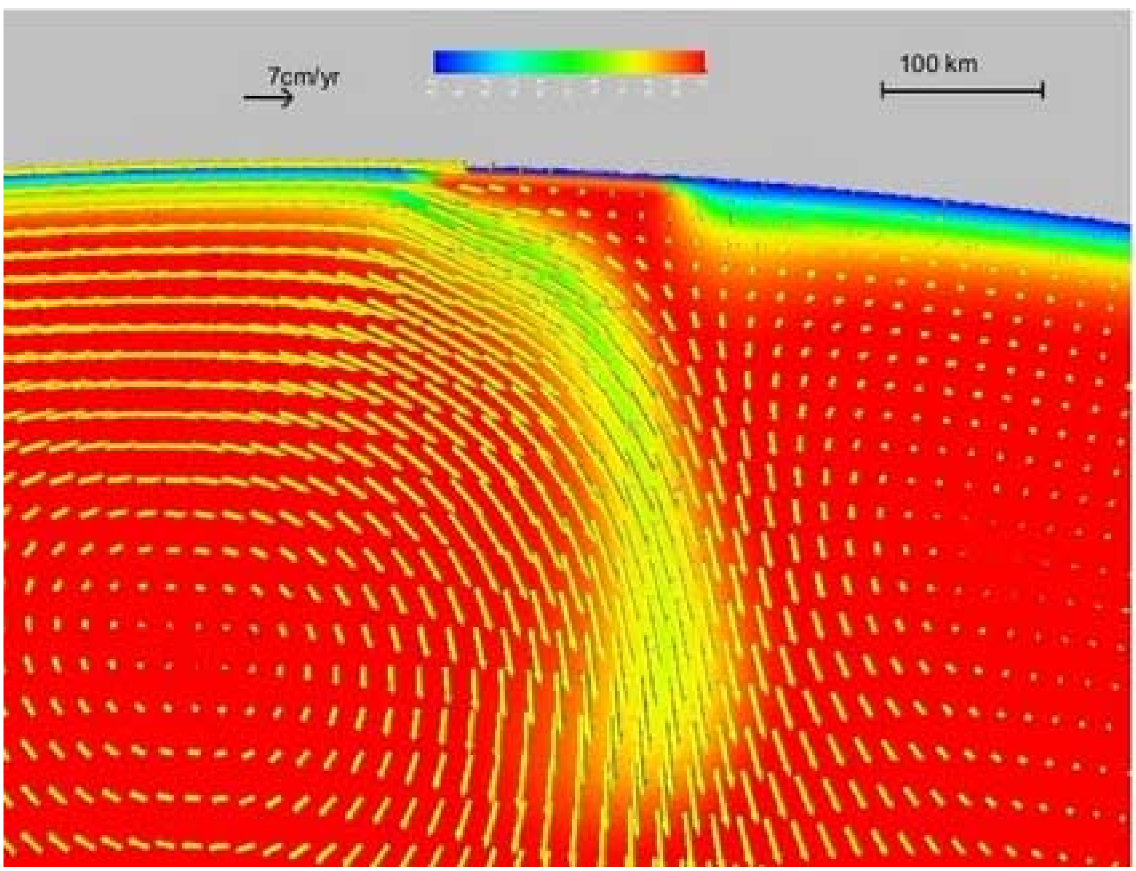

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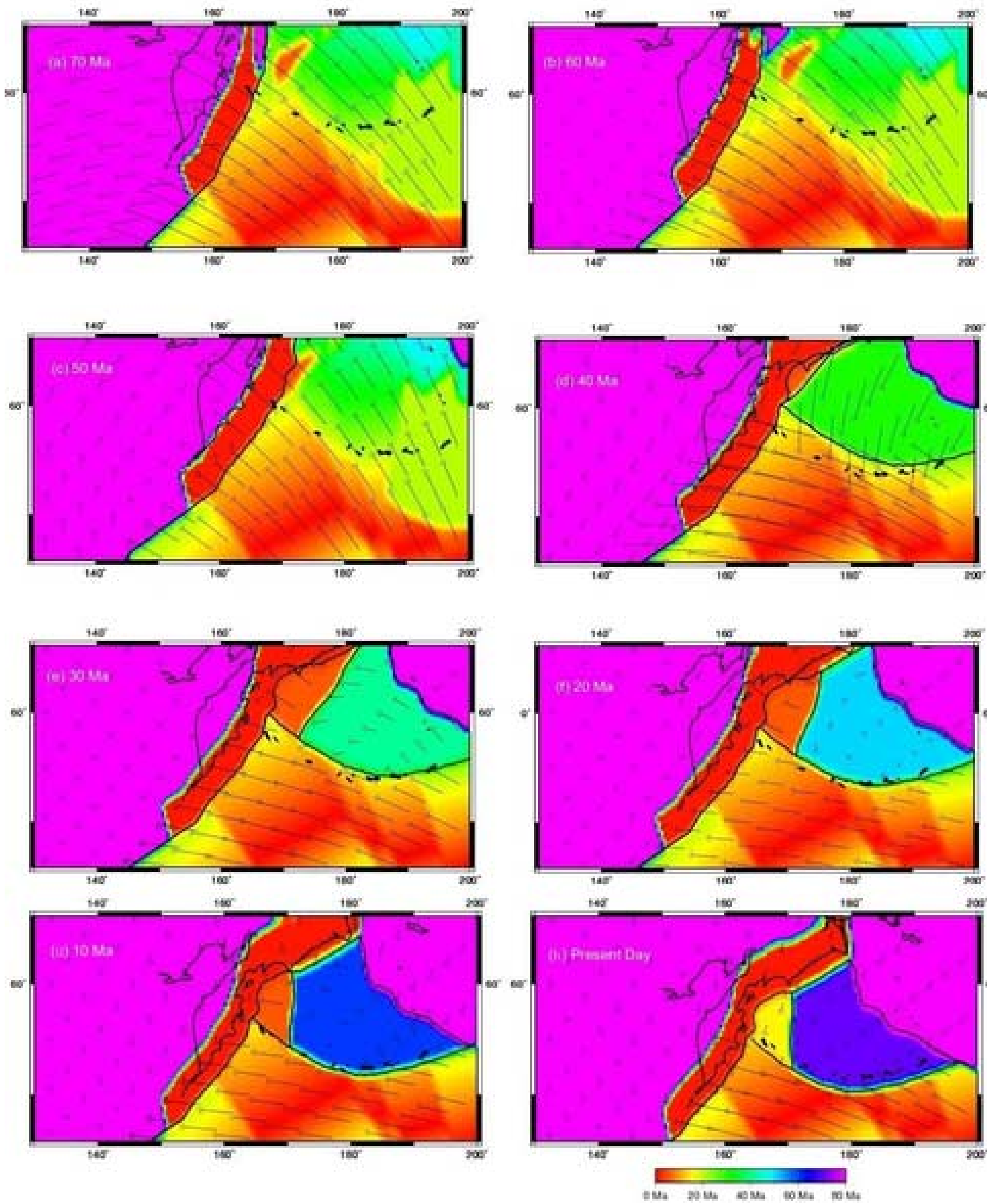

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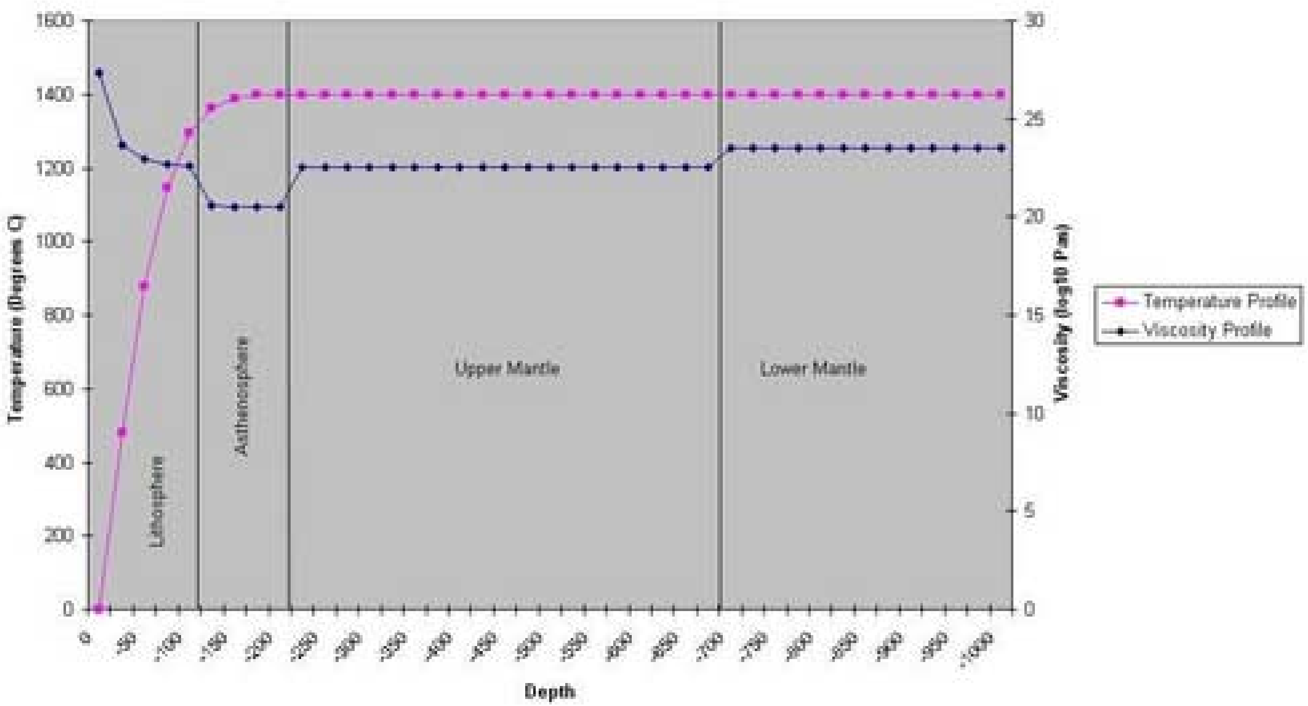

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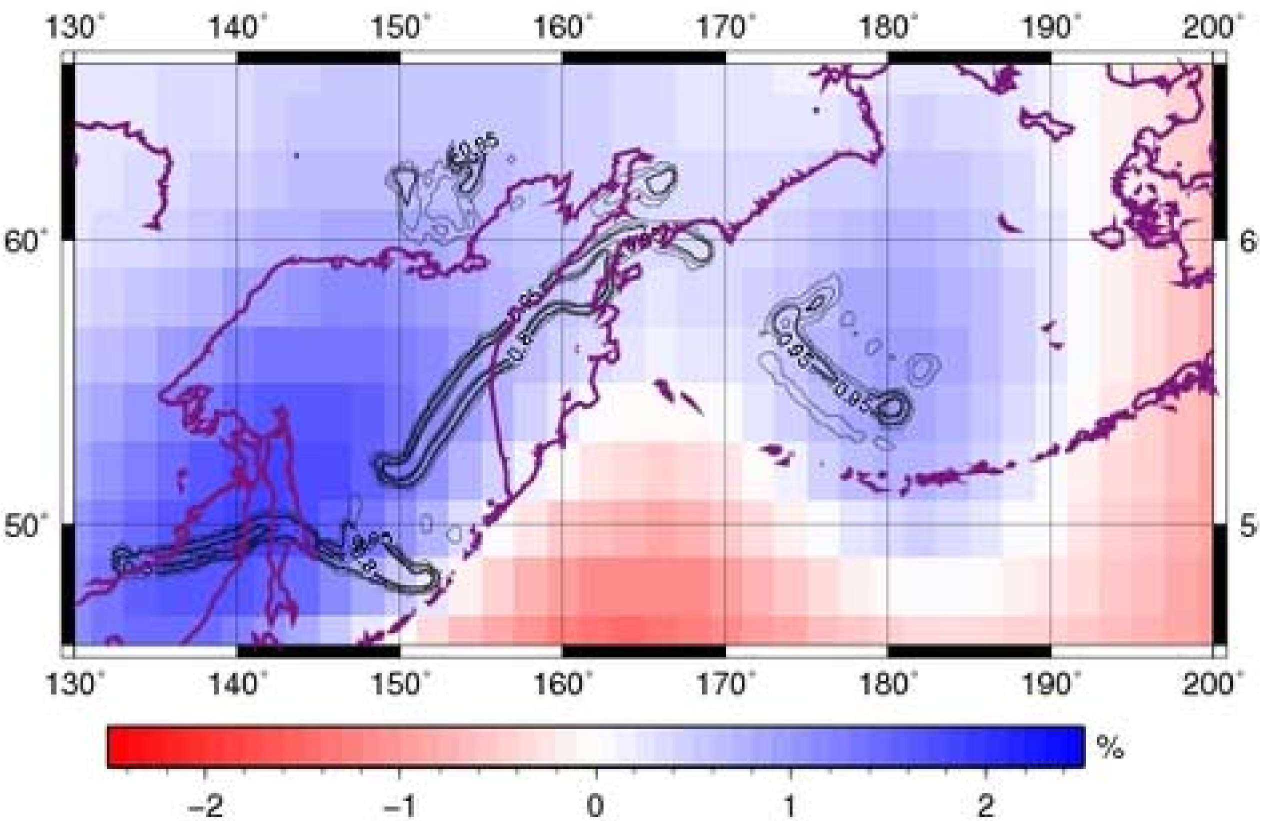

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