Three-dimensional thermal modeling for the Mendocino Triple Junction area

Saskia Goes a,*, Rob Govers b, Susan Schwartz c, Kevin Furlong d

a Department of Geological Sciences, University of Michigan, 1006 C.C. Little Building Ann Arbor, MI 48109-1063, USA
b Institute of Earth Sciences, Department of Geophysics, Utrecht University, P.O. Box 80021, 3508 TA Utrecht, The Netherlands
c W.M. Keck Seismological Laboratory and Earth Science Department, University of California, Santa Cruz, CA 95064, USA
d Department of Geosciences, Penn State University, University Park, PA 16802, USA

Received 22 October 1996; revised 20 February 1997; accepted 20 February 1997

Abstract

Complex interaction between the Pacific, North American, and Juan de Fuca plates at the northward migrating Mendocino Triple Junction (MTJ) has had a profound effect on the geological evolution of western North America. This paper presents a three-dimensional thermal model for the area around the MTJ that is based on its kinematic evolution, incorporating the effects of an asthenospheric slab window, changes in relative plate motions and the trenchward migration of the Juan de Fuca-Pacific spreading ridge. The thermal equation, including conductive and advective heat transport, is solved numerically using finite differences. Surface heat flow data and the trend in the maximum depth of seismicity south of the MTJ can be quite well explained by the thermal model. A finite lithospheric thickness above the slab window is required to fit heat flow measurements; however, the lack of data west of the San Andreas Fault prevents discriminating between underthrusting and accretionary mechanisms of lithospheric thickening. A comparison between the thermal and recent seismic velocity models reveals that P-wave anomalies in the uppermost mantle have smaller wavelengths and larger amplitudes than predicted if they were purely thermal.

Keywords: Mendocino triple junction; thermal evolution; three-dimensional model

1. Introduction

The Mendocino Triple Junction (MTJ, Fig. 1) was formed about 30 Ma, when part of the Pacific–Farallon ridge system reached the North American Trench (e.g., [1]). The MTJ migrated to the northwest, while its southern counterpart, the Rivera Triple Junction, moved southeast. Between the two triple junctions subduction was replaced by translational movement of the type observed along the San Andreas Fault system today. As the Juan de Fuca plate moves to the northwest, a slabless window is left in its wake and filled with upwelling, hot, asthenospheric material [1-3] (Fig. 2). The asthenospheric material gradually cools and accretes to the Pacific and North American plates. The changing mechanical behavior of the material in the slabless window in space and time controls the evolution of the Pacific–North American plate boundary at subcrustal depths and is
responsible for the complex patterns of faulting (e.g., [4]), crustal deformation and volcanism (e.g., [5]) observed in association with the San Andreas Fault system (discussed by e.g., [1–3]).

Opening of the slabless window during evolution of the MTJ should leave a strong thermal signature. Evidence for the shallow emplacement of hot material has been found in surface heat flow [6], gravity anomalies [7], tomographic models of P-wave velocities [8–11], and variations in the depth of seismicity (e.g., [12]). These thermal effects have been explored using one- and two-dimensional geometries [6,13–15], but a full understanding of the evolution of the asthenospheric slab window requires three-dimensional thermal modeling. This allows for a more accurate representation of the triple junction geometry, including the cooling effect of the slab north of the window and three-dimensional kinematics of the asthenospheric material; it also allows a better comparison with two- and three-dimensional data sets (e.g., [6,9,12]).

One- and two-dimensional models have shown that an average lithospheric thickness of 20–40 km above the window is required to fit the surface heat flow data [6,13,14]. In three dimensions it is necessary to model how this lithospheric thickness above the window evolves from the subduction geometry before passage of the triple junction. Extension of the Pacific plate east of the trench under North America is a plausible mechanism for preventing hot asthenosphere from upwelling under the thinnest part of the North American plate. Tomographic images [9,10] and seismic reflection/refraction profiles just south of the triple junction [16] and in central California (e.g., [17,18]) provide evidence that high velocity material underlies the coast of North America, extending as far east as the San Andres and possibly as far as the Maacana–Rodgers Creek–Hayward fault zone (Fig. 1) south of 38.5°. High velocity anomalies extend 60–100 km east of the position of the paleosubduction zone offshore. Several mechanisms have been proposed to explain why high velocity material is present under the western edge of North America. It may be the result of overthrusting of the North American plate during Basin and Range extension [17], of compression due to a change in Pacific–North American plate motions [17,18], of welding of already underthrust remnants of the Farallon/Juan de Fuca plate to the Pacific plate [19], and/or by accretion of slab window material to the Pacific plate [3]. We investigate the thermal consequences of the different scenarios and compare the resulting thermal structures with surface heat flow, the depth distribution of seismicity and 3-D tomographic images of P-wave velocities.

2. Numerical model

The modeling focuses on two end-member scenarios for slab window kinematics. Upwelling of hot asthenosphere under the thinnest part of North America is prevented by either underthrusting (Pacific) oceanic plate beneath North America prior to model initiation, with no convergence occurring during model evolution (underthrusting model A), or by accreting asthenospheric material to the eastern edge of the Pacific plate during thermal evolution of the model (accretion model B). In addition to the kinematics of the material in the window, the thermal structure is affected by the (variation in) age of the
subducting Juan de Fuca slab, and changes in relative plate motions. By prescribing the plate configuration and velocities and adjusting initial and boundary conditions the thermal effects of the tectonic evolution of the Mendocino Triple Junction are modeled.

2.1. Numerical procedure

Temperatures in the model are calculated by solving the 3-D isotropic thermal conduction–advection equation numerically. In prescribing slab window kinematics the effects of convection within the window are neglected. Liu and Furlong [14] conclude from 2-D thermal modeling that the geometry of the shallow slab window precludes significant small-scale convection. Zandt and Carrigan [20] and Liu and Zandt [15] propose that convective instabilities do evolve in the slabless window, as the cooling asthenosphere forms an unstable boundary layer on a time scale of 15–25 m.y. The part of the slab window included in our model has not cooled long enough to start developing these large-scale convective instabilities. The conductive part of the thermal equation is solved using a 3-D finite difference method [21–23]. The omission of the advective term is corrected for by moving, at specified time steps, each point in the grid at the corresponding plate velocity and subsequently interpolating temperatures back to the grid on which the conductive equation is solved. Values of the material parameters used are listed in Table 1.

2.2. Geometry

The model plate configuration is illustrated in Fig. 2. North of the triple junction the Juan de Fuca slab dips at a constant angle of 15° beneath North America. At present the Juan de Fuca plate just north of the MTJ subducts beneath North America at an angle of 11° [7,11,16]. This dip may have been larger in the past when the subducting slab was older and less buoyant. In all model runs the trench and the transform boundary line up at the surface. This is a simplification of the real geometry where there is a misalignment between the coast-parallel trench and the trend of the San Andreas transform fault (Fig. 1). Fig. 2 shows the geometry for the underthrusting model A. In accretion models, the Pacific-window boundary is vertical and below the position of the trench.

Table 1

<table>
<thead>
<tr>
<th>Material parameter values used in the model</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Density: specific heat</td>
<td>(J/m³/K)</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>(W/m/K)</td>
</tr>
<tr>
<td>Continental surface heat production</td>
<td>(W/m²)</td>
</tr>
<tr>
<td>Characteristic depth for exponential decay of continental heat production</td>
<td>(km)</td>
</tr>
<tr>
<td>Basal heat flow</td>
<td>(mW/m²)</td>
</tr>
<tr>
<td>Thermal expansion coefficient (oceanic)</td>
<td>(1/K)</td>
</tr>
</tbody>
</table>
2.3. Kinematics

In order to obtain a realistic present day thermal structure we let the model evolve starting 15 Ma. In the last 15 m.y., the development of the slabless window in central and northern California has been relatively simple (e.g., [24]). The North American plate in the model is kept fixed while the Pacific and Juan de Fuca plates move parallel to the trench/transform boundary at same velocity $V_p$ (Fig. 2). The change in Pacific relative motion at 10 Ma [1,25] is included by increasing $V_p$ from 22 mm/yr to 52 mm/yr. In addition to the trench-parallel motion of $V_p$, we also let the Juan de Fuca plate subduct beneath the North American plate with a constant velocity of 20 mm/yr (= $V_{\text{spread}}$). The spreading velocity, $V_{\text{spread}}$, of the Juan de Fuca plate decreased over the last 15 m.y., but the velocities of the southern end of the Juan de Fuca plate are not well enough constrained to warrant varying this velocity in the model (see [26–28]). A change in plate motions about 3 Ma that caused internal deformation of the southern part of the Juan de Fuca plate (also called the Gorda deformation zone, Fig. 1) [29] and may have caused a change in orientation of the southern edge of the Juan de Fuca/Gorda plate [7,11], is not included in the model because it is a secondary effect in the larger scale thermal structure presented here.

The rigid motions of the Pacific, North American and Juan de Fuca plates are well constrained [1,25,27,28]. The kinematics of the material within the window, however, are a function of temperature, as the distribution of Pacific–North American strain within the window depends on the rheology of the asthenospheric material [3]. Various simple, temperature-dependent velocity fields were tested to simulate different rates of Pacific–North American strain localization during cooling. We discuss the results of Model A, an underthrusting model without accretion, where velocity of the slab window material varies linearly between $V_p$ and 0 over $x$ in the window (Fig. 2, bottom left), and Model B, an accretion model (Fig. 2, bottom right) where window material starts moving with the velocity of the closest rigid plate as soon as the temperature falls below a critical temperature ($T_{\text{crit}}$). Where the window material moves at velocities less than $V_p$ the space created behind

Fig. 3. Evolution of the thermal structure illustrated by horizontal cross sections at 50 km depth through Model A. Temperatures are illustrated by a gray scale as well as thin contours every 100°C and bold contours every 500°C.

the Juan de Fuca slab is filled by material of mantle temperature (1300°C) to simulate asthenospheric upwelling.

2.4. Initial and boundary conditions

Initial temperatures (at 15 Ma, Fig. 3, left) within the oceanic lithosphere of the Juan de Fuca and Pacific plates are based on age estimates from magnetic anomalies [1]. They are set to 1300°C (mantle temperature) within the slabless window and follow a steady state geotherm, with heat production exponentially decaying with depth in the North American plate ([30], pp. 145–146, parameter values in Table 1). Boundary conditions for the conductive part of the equation include a constant temperature at the surface, zero heat flow through the sides of the box (this implies an assumption of no major variations in thermal structure outside of the model box) and a constant basal heat flux. Advecive boundary conditions for material entering the box at the southern end of the Pacific plate and the slabless window again assume no variation outside of the box (i.e.
\(dT/dy = 0\). The thermal structure of the material entering the western side of the model is dependent on the age of the Juan de Fuca plate, which is a function of the position of the Gorda ridge (Fig. 1). The ridge migration that has taken place over the last 40 Ma [26] is modeled by gradually moving the ridge from a position 525 km west of the trench at 15 Ma to 225 km from the trench at 0 Ma.

3. MTJ area thermal model

3.1. Model evolution

Fig. 3 shows the evolution of the thermal structure for Model A in which the Pacific plate extends 60 km beyond the former trench underneath the North American plate. This model illustrates the main features of the thermal structure and is consistent with geophysical observations, as discussed in Section 4. The most conspicuous feature in the evolution of the thermal model through time is the hot anomaly associated with the slabless window. The anomaly lengthens as the triple junction moves in the \(y\) direction and the length increases faster after the increase in velocity at 10 Ma. The asymmetric wedge shape of the slabless window anomaly results from the difference in thermal structure between the quite young and hot Pacific plate on the west side and the cooler North American continental lithosphere on the east side. This model and other model runs indicate that the thermal structure in both the slab and the window reaches a dynamic equilibrium about 5–6 m.y. after the last change in velocity. Thus the initial 5 m.y., where the plates move at lower \(V_p\), suffice to set up an ‘initial’ thermal structure that is a reasonable approximation of the equilibrium structure due to the conditions before 10 Ma and the final 10 m.y. are long enough to reach a new equilibrium after the change in plate motions. The velocities within the slabless window may change within this time frame according to the changing thermal structure, but models with different window kinematics indicate that these changes are small enough to have little effect on the stability of the major features (e.g., the geometry of the slab window anomaly) of

![Fig. 4. Selected vertical cross sections through the present day thermal structure predicted by Model A, and Model B. Isotherms as in Fig. 3. Solid black lines represent the location of plate boundaries.](image-url)
the final model. Different boundary and initial conditions were also tested and found to have only minor effects on the resulting thermal structure, except for some effect of the initial slab window temperature at the southern end \((y < 100\ \text{km})\) of the model (Fig. 3).

3.2. Present day thermal models

Fig. 4 shows the present day thermal structure for both Model A and B (no underthrusting, \(T_\text{crit} = 1100\degree\text{C}\)) in several east–west cross sections. The top two cross sections of both models illustrate the warming effect of the upwelling asthenospheric material on the slab just north of the triple junction (located at \(y = 680\ \text{km}\)). The cross sections south of the triple junction (TJ) show the evolution of the thermal structure within the slabless window. A clearly defined window with shallowly emplaced hot material at \(y = 600\ \text{km}\) develops into a slightly dipping structure at \(y = 200\ \text{km}\), where the signature of the underthrust Pacific/accreted material and the hot asthenospheric material have been smoothed out by thermal diffusion. Model A has a slightly cooler slab just north of the window \((y = 700\ \text{km})\) than Model B. The main difference between the models, however, is the slab window anomaly. In Model A the window has a clear western edge, due to the cold anomaly associated with the underthrust Pacific plate. In Model B the western edge of the window anomaly is not clearly defined as the smaller thermal contrast between the Pacific plate and the material accreted to it diffuses while the accreted material moves with the plate. Cooling of the asthenospheric material on the Pacific side is mainly the result of an insulation effect: as material moves with velocities close to \(V_p\), little to no upwelling of hot asthenosphere can occur allowing the initially hot Pacific plate to slowly lose heat. On the North American side of the window the thermal contrast between the asthenosphere and the cold continental lithosphere is large enough to result in faster cooling of the window material.

4. Comparison of thermal models with geophysical data

To assess how much of the geophysical observations can be attributed to a thermal signature and attempt to discriminate between thermal models A and B, the models are compared with surface heat flow, the distribution of seismicity and a tomographic P-wave velocity model. In order to make a comparison with observations it is necessary to locate the surface characteristics of the Mendocino area relative to the modeled plate boundaries at depth. To account for the difference in trench–transform orientation, we align model cross sections north of the triple junction \((y > 680\ \text{km})\) with east–west sections through the data and cross sections south of the triple junction \((y < 680\ \text{km})\) with data cross sections perpendicular to the San Andreas Fault. One effect of the extension of the Pacific plate east of the trench (either by underthrusting or by accretion) is that the deep plate motions are localized east of the position of the previous surface boundary at the trench. Over time it is more favorable if the surface boundary jumps eastward to align with the localization of strain at depth. In the tomographic models [9,10] the high velocity anomaly that may be attributed to the presence of cold material at depth may extend as far east as the Maacama–Rodgers Creek fault zone (Fig. 1) about 40 km east of the San Andreas. Thus the San Andreas probably corresponds to a model \(x\) coordinate between 95 and 135 km. In the comparisons, the position of the San Andreas is aligned with \(x = 135\ \text{km}\), the position of the Pacific-window boundary in Model A. In the cross sections north of the triple junction the coastline is aligned with \(x = 125\ \text{km}\), where the top of the slab is located at about 10 km depth in the models (to be consistent with the position of the top of the slab, as inferred from tomographic modeling [11]). We concentrate the comparison on the area 100 km north to about 400 km south of the triple junction.

4.1. Surface heat flow

Surface heat flow is a very direct result of the thermal structure at depth. The heat flow data compiled by Lachenbruch and Sass [6] show an anomaly along the trend of the San Andreas Fault which reaches a maximum at 200 km south of the MTJ, with a rapid decrease toward the MTJ and a slow fall-off southward (Fig. 5). This trend has already been modeled as the result of upwelling hot asthenosphere underneath thin lithosphere [6,13]. The ampli-
Fig. 5. Comparison of heat flow observations compiled by Lachenbruch and Sass [6] and surface heat flow from the 3-D thermal models averaged over a band from 5 to 100 km ($x = 140-240$ km) east of the San Andreas Fault (which is assumed to be aligned with the eastern edge of the Pacific plate in Model A, at $x = 135$ km). The data can be matched by both Model A (solid line) and B (dashed line).

Attitude and position of the maximum place constraints on the thickness of the overlying lithosphere, and in the case of the 3-D thermal models on the amount of underthrusting or accretion required. The heat flow data in Fig. 5, which are averaged over a region about 100 km wide perpendicular to the San Andreas, are consistent with heat flow predicted both by Model A and Model B. The crustal thickness above the slabless window in Model A varies from 16.8 km ($x = 140$ km) to 42.7 km ($x = 240$ km), consistent with the 20–40 km crustal thickness estimates from 1-D and 2-D modeling [6,13,14]. In Model B a similar effective lithospheric thickness results from accretion, where the final thickness is controlled by the thickness of the Pacific plate.

Cross sections perpendicular to the San Andreas Fault show a decrease in heat flow away from the fault (Fig. 6). Both thermal models fit this trend. North of the triple junction the models do not differ and are consistent with the few heat flow observations there. Note that some values measured in areas with thick sediment layers, such as the Eel River Basin (just north of the MTJ, in H1) and in the Great Valley (at the eastern edge of H3 and H4) may be biased low [6]. The high outlier in profile H4 was measured at the Geysers geothermal area and is not included in the average in Fig. 5 [6]. Although there is a lot of scatter in the heat flow values measured, these data give no indication that models and data...
should be aligned with the Maacama fault system instead of with the San Andreas. Unfortunately, the heat flow data do not allow for a discrimination between the two models because there are few measurements west of the San Andreas Fault where Model A and B predict significant differences in the surface heat flow.

4.2. Seismicity

4.2.1. Depth of seismicity

The maximum depth of seismicity is thought to be controlled by the transition from unstable (seismic) to stable (aseismic) sliding ([31,32] pp. 125–133). The stability of frictional sliding depends on pore pressure, rock type, porosity, gouge layer thickness and size, but more importantly on temperature and effective normal pressure [31]. For oceanic lithosphere the correlation between maximum depth of seismicity and the 600–800°C isotherm has been long recognized (e.g., [33]). For a continental setting the correlation with temperature is less clear because the composition and stress distribution in the continents are more complex than in most oceanic plates. Several authors (e.g., [31,34]), however, have correlated the maximum depth of seismicity in continental crust with the 300°C isotherm, with specific work for the San Andreas Fault done by Miller and Furlong, and Furlong and Atkinson [35,36].

The depth above which 90% of the seismicity occurs was determined for earthquakes with magnitudes ≥ 2 south of the MTJ, as recorded and located by the NCSN (Northern California Seismic Network) between 1974 and 1994, and for relocated earthquakes (see next section) with location errors less than 2 km for the area north of the triple junction. Fig. 7 shows the contour of the 90% depth of seismicity for several cross sections through the slab and perpendicular to the trend of the San Andreas Fault. Plotted on top of these cross sections are the 600–800°C (north of the triple junction) and 200–400°C isotherms (south of the MTJ) from Models A and B. The misfit between the depth of seismicity and the isotherms in the subducting slab may be the result of a shallower slab dip (10° rather than 15°) and/or warming, due to a break in the slab, as is suggested by tomographic images ([9], Fig. 8). South of the triple junction the 90% depth can be

Fig. 7. Comparison of the depth above which 90% of the seismicity falls with model isotherms. North of the MTJ (cross section S1) seismicity data are events from the NCSN catalog (1974–1994) relocated in a 3-D velocity model constructed from the onshore velocities of Verdonck and Zandt [11] and offshore velocities from the Mendocino Working Group (A. Trehu, pers. commun., 1995). The contour for the 90% depth (bold line) of seismicity is only shown where the intervals contain at least 10 events. Isotherms (solid for Model A, dashed for Model B) in the slab north of the MTJ are for 600°C, 700°C and 800°C. Plate boundaries are shown by the thinnest lines and coincide for both models, except the Pacific-window boundary. South of the triple junction (cross sections S2–S4), seismicity includes all events M ≥ 2 from the NCSN catalog and isotherms of 200°C, 300°C and 400°C are shown.
explained by the thermal structure. Both the seismicity data (Fig. 7) and the heat flow profiles perpendicular to the San Andreas Fault (Fig. 6) lend support to the slab window geometry chosen in the models. The seismicity data are consistent with the alignment of models and data at the San Andreas Fault (Fig. 7); however, alignment with the Maacama–Rodgers Creek fault zone would not result in a significantly different fit. Again, the lack of seismicity west of the San Andreas precludes distinguishing between the two models. The few events that are located west of the San Andreas (e.g., [12,37]) may indicate a deepening of seismicity westward but this trend is poorly constrained.

4.2.2. Relocated seismicity north of the MTJ

The seismicity pattern north of the MTJ has been interpreted as showing a 'double' seismic zone with depth in the Juan de Fuca slab offshore of Cape Mendocino [38]. Uncertainties in the offshore locations can be quite large, especially in depth, due to the one-sided distribution of seismic stations (all on-land). Since the study by Smith et al. [38] improved resolution of onshore [11] and offshore (Mendocino Working Group, Anne Trehu, pers. commun., 1995) seismic velocities have been attained. To verify the pattern of seismicity and to test if the pattern is compatible with our predicted thermal structure, we have relocated earthquakes in the region north of the MTJ. Seismicity recorded between 1974 and 1994 by the Northern California Seismic Network (NCSN) was relocated using a joint relocation–velocity inversion method for local earthquakes [39–41] and a 3-D velocity structure that combines the onshore and offshore velocity models. One result of the relocation is that we do not find a double seismic zone. This is consistent with relocation tests performed by Oppenheimer (pers. commun., 1995) who concluded the double seismic zone was probably an artifact.

4.3. Tomographic images of P-wave velocities

Evidence for the presence of shallow hot material under the Northern California Coast Ranges has also been seen in tomographic inversions of teleseismic P-wave arrival times [8–10]. In the crust seismic velocities are probably largely controlled by compo-
sition: in the mantle, however, temperature is thought to be the dominant factor. Experimentally determined values of bulk and shear moduli and their derivatives with pressure and temperature for forsterite give velocity changes with temperature of \( \frac{dV_p}{dT} = 0.5 - 0.6 \text{ m/s/°C} \) [42] for the depth range considered here. However, if anelasticity plays an important role, the temperature derivative may be as high as \( 1.0 \text{ m/s/°C} \) [43] and close to the melting temperature \( dV_p/dT \) may increase to \( \approx 3 \text{ m/s/°C} \) [44].

To compare 3-D thermal and tomographic models, temperatures were averaged over a range in depth similar to the block size of the tomographic models, and thermal anomalies relative to the average temperature in the depth range considered were scaled using \( dV_p/dT = 0.5 \text{ m/s/°C} \).

The top-most mantle layer (30–70 km) of the tomographic P-wave velocity model of Benz et al. [9] shows a wedge-shaped low velocity anomaly south of the MTJ and east of the Maacama–Rodgers Creek fault zone (Fig. 8). The shape of this low velocity anomaly is similar to the high temperature slab window anomaly in Model A (Fig. 3). The size of the slab window, when measured as the length and maximum width of the \( dV_p = -1\% \) contour, is similar for the thermal and tomographic velocity models. The anomaly has a maximum width of about 100 km in Model A and about 130 km in the tomographic images. The thermally predicted length is 500–600 km, compared to a seismically imaged length of around 450 (using the tomographic model from Zandt [8]). Model B lacks the lower temperatures west of the slab window and thus does not produce the same wedge-shaped anomaly. However, the high velocity anomaly that underlies the coast of California west of the slab window anomaly (Fig. 8) lies on the edge of the well resolved part of the tomographic model. A comparison that takes into account the variations in resolution of the tomographic images (e.g., [45]) should be done to fully assess the discrepancy with Model B.

Other velocity anomalies produced by the thermal model are low velocities under the offshore part of the (young) Juan de Fuca plate, and a high velocity anomaly associated with the subducted Juan de Fuca slab. Both anomalies are also seen in the tomographic inversion (Fig. 8), although the Juan de Fuca slab anomaly is very small and extends much less eastwards than would be expected for a continuous slab. The easternmost high velocity anomaly in the tomographic model (Fig. 8) extends to a depth of 250 km [9] and has been attributed to either broken pieces of the former Farallon slab [9,10] or downwellings resulting from convective instabilities [15,20]. At the shallow mantle depths considered here, a lower amplitude high velocity anomaly is predicted by the thermal models (Fig. 8, sections V2–V4) and is associated with the cold North American plate.

Differences between thermal and tomographic models are best illustrated in cross section (Fig. 8, bottom). The two thermal models A and B show relatively small differences; however, the thermally predicted velocity anomalies are smoother and lower in amplitude than the tomographic anomalies. The tomographic model from Benz et al. [9] has fast velocity anomalies \( dV_p \) of up to +9.5\% and slow anomalies up to −5.8\% in the depth layer at 30–70 km (layer 3). \( dV_p \) in layer 4 (between 70 and 110 km) ranges from +5.8\% to −3.7\%. Thus, temperature ranges necessary to produce the range in imaged \( dV_p \) values are 1200–2400°C for layer 3 and 950–1900°C for layer 4. The average model temperature in the depth range of layer 3 is about 850°C in both models and the maximum temperature is about 1300°C. The effect of the melting temperature [44] could enhance the amplitude of the thermal low velocity anomaly and, if anelasticity affects \( dV_p/dT \), the amplitude of the thermal high velocity anomaly could also be higher. However, if the slab window anomaly was purely thermal, it would be expected to decrease in amplitude and become smoother southwards. This pattern is not apparent in the tomographic model. The tomographic model shows a lot more heterogeneity than thermally predicted. Thus, changes in composition, anisotropy or the presence of partial melt are probably important.

5. Discussion and conclusions

We presented the 3-D thermal effects of the evolution of the Mendocino Triple Junction. The thermal modeling takes into account the well documented plate kinematics, including the effects of the north-
ward migrating asthenospheric slab window, a change in northward velocity of the Pacific plate at 10 Ma and migration of the Gorda ridge toward the trench. The 3-D thermal structure obtained is consistent with surface heat flow observations, variations in the maximum depth of seismicity south of the MTJ, and, to first order, with the slab window anomaly seen in tomographic images of seismic P-waves. To compare the models with data, the trace of the San Andreas Fault was aligned with the boundary between the Pacific plate and the slab window at depth (Model A and with the same x coordinate in Model B). This gives a reasonable fit between models and data. However, given the scatter in the data and the fact that the observations are not only sensitive to temperature, alignment of the deep 'plate boundary' just south of the MTJ with surface fault systems east of the San Andreas cannot be ruled out. A maximum depth of seismicity shallower than the 600°C isotherm of the thermal model north of the triple junction indicates that the subducting slab north of the triple junction is warmer than predicted by the models. This could be due to either a smaller slab dip or be the effect of a discontinuous slab, as suggested by tomographic models [9,10]. Since the thermal models under-predict both the amplitude and the complexity of the tomographic images, variations in composition below the crust, the presence of partial melt or significant anisotropy must be important.

Especially important for the final thermal structure are the temperature-dependent kinematics of the material in the asthenospheric window because they describe the evolution of the Pacific–North American plate boundary at depth. Two model categories are consistent with geophysical observations for the Mendocino Triple Junction area: (1) models with significant initial underthrusting of the Pacific plate and no accretion to the Pacific; (2) moderate rate accretion models without any initial underthrusting. The first category includes models that look similar to Model A and can range from very low \( T_{\text{crit}} \) (Fig. 2), that is, no strain localization on time scale of model; to very high \( T_{\text{crit}} \), that is, strain localizes almost instantly on the Pacific, hottest, side of the window. About 60–100 km underthrusting, for a slab dip between 8° and 15°, is required to explain the geophysical data and this amount of underthrusting is consistent with the present-day offset between the trench and the San Andreas Fault. Using steeper dips results in a narrower slab window, which is inconsistent with the width of the low velocity anomaly found from tomographic inversions [9,10].

Models in the second category show similar features to Model B. These models can fit the surface heat flow by having temperature-dependent accretion of asthenospheric material occur slow enough to allow for cooling of, and thereby accretion of, material on the Pacific side and fast enough to occur on the time scale of the evolution of the slab window. With our simple parametrization of slab window kinematics, significant accretion of slab window material to the Pacific plate within the evolution time of the model only occurs for a narrow range of critical temperatures, 1000–1100°C. Full 3-D thermo-mechanical modeling (e.g., [3]) would be necessary to model the accretion process more accurately. A few remarks can, however, be made based on our simple accretion models. Accretion of material to the Pacific plate which is young and warm compared to the North American plate is not very effective and the depth of accretion is controlled by the relatively thin Pacific plate. In models where a partially underthrust Pacific is combined with significant accretion, the thickness of the cold layer overlying the slab window could extend deeper. However, the amount of underthrusting has to be small in order to fit the heat flow data.

Although the two scenarios predict significant differences in thermal structure, the available geophysical data do not allow us to rule out Model A or B. As the main difference in thermal structure is located near the eastern edge of the Pacific at depth, more observations west of the San Andreas could resolve whether underthrusting or accretion is the main process responsible for cold material under the western edge of the North American plate. Although the tomographic anomalies are more consistent with the thermal features of Model A, the tomographic images reflect a significant non-thermal signature. Resolution tests on the offshore anomalies in the tomographic models should be carried out, for example using the thermal models to create synthetic velocity models (e.g., [45]). The modeling of one of the fundamental physical properties, temperature, that plays a role in the tectonics of the MTJ area can thus be used as a basis for further studies of the area.
Acknowledgements

We thank Harley Benz, David Verdonck and Anne Trehu for their seismic velocity models and the Northern California data center for providing the locations and phase readings of the earthquakes used in this study. We also thank Tanya Atwater and an anonymous reviewer for their constructive criticism of the paper. This research was partially supported by U.S. Geological Survey award 1434-94-G-2494 to SYS and NSF-EAR 9628347 to KPF. [UC]

References


