Ephemeral crustal thickening at a triple junction: The Mendocino crustal conveyor

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ABSTRACT

As the North American crust interacts with the migrating Mendocino triple junction, the crust is first significantly thickened and then equivalently thinned over a distance of a few hundred kilometers (within a time frame of 5 m.y. or less). This process of ephemeral crustal thickening is proposed to result from viscous coupling between the northward-migrating Gorda slab and the base of North America south of the triple junction. A time-dependent, thermal-mechanical finite-element model is developed to test this hypothesis of plate-boundary tectonics. Results of the numerical simulations show patterns of crustal deformation consistent with the mapped sequence of folding and faulting in the area, the observed crustal structure and triple junction regional seismicity, and localized regions of crustal extension coincident with the position of a hypothesized lower-crustal melt zone.

INTRODUCTION

The Mendocino triple junction represents a location of profound change in plate tectonic processes. The transition from convergence (north of Mendocino) to translation (south of Mendocino) is abrupt, and its impact on the North American plate is substantial. The tectonic model of a slab window that develops on the lithospheric scale at the Mendocino triple junction (e.g., Dickinson and Snyder, 1979; Zandt and Furlong, 1982; Furlong, 1993) implies that the base of North America is exposed to mantle material which upwells south of the triple junction. This model of lithosphere evolution satisfies regional geophysical and petrological observations such as heat flow (Lachenbruch and Sass, 1980; Furlong, 1984; Goes et al., 1997), volcanism (Liu and Furlong, 1992; Dickinson, 1997), and mantle tomography (Benz et al., 1992; Furlong, 1993; Goes et al., 1997). Crustal-structure (Verdonck and Zandt, 1994; Beaudoin et al., 1996) and seismicity patterns (Miller and Furlong, 1988; Castillo and Ellsworth, 1993) indicate that the crustal response to triple junction passage is more complex than assumed in the passive slab-window model. In particular, there is a substantial variation in crustal thickness associated with passage of the triple junction.

Of the tectonic aspects of the Mendocino triple junction area (Fig. 1), most important is the development of a region of localized crustal thickening (Verdonck and Zandt, 1994; Beaudoin et al., 1996) that straddles the triple-junction area. If it is linked to the triple-junction process, this crustal welt must migrate with the triple junction, involving processes that thicken the crust ahead of the triple junction and thin the crust in its wake. Seismic tomography (Verdonck and Zandt, 1994) and reflection and wide-angle refraction imaging (Beaudoin et al., 1996) show evidence of significantly thicker crust (~30+ km) in a region extending approximately 50 km north and south of the southern edge of the Gorda slab. Further north and south of the triple junction the crustal thickness is <20 km. The location of the southern edge of the Gorda plate is uncertain (for consistency with most previous work in the region, we will use the term *Gorda* to signify the southern part of the Juan de Fuca plate). It was interpreted by Jachens and Griscom (1983) to be along the southern gradient of the isostatic residual gravity anomaly that straddles the region (Fig. 1). Analyses of seismicity (Castillo and Ellsworth, 1993; McPherson, 1989) and seismic structure (Verdonck and Zandt, 1994; Beaudoin et al., 1996) place the southern edge of the Gorda slab north of the position inferred by Jachens and Griscom (1983) with a more eastward strike (Fig. 1). There is a region of reduced seismicity (Castillo and Ellsworth, 1993) that is located between these two estimates.

In the typical orogenic cycle, plate convergence drives deformation, crustal thickening, and uplift; crustal thinning and related elevation decay are normally a consequence of erosion or other surface geomorphic processes. The evolution of the crust of the Coast Ranges in northern California differs from that model in that crustal thickening is driven by plate motions; the subsequent crustal thinning is not primarily erosional, but rather, is internal to the crust and is driven by plate-tectonic processes that only a few million years previously had thickened the crust. We hypothesize that the crustal welt beneath the Coast Ranges of northern California is produced by a sequence of crustal thickening and then thinning associated with triple junction passage.

CONCEPTUAL MODEL

At the Mendocino triple junction, in the slab-window model, mantle material flows into the region vacated by the Gorda plate, which translates to the north-northwest. Geodetic observations (Mitchell et al., 1994) and modeling (Verdonck, 1995) indicate that full coupling between the Gorda plate and North America extends from the offshore deformation front to approximately the coast line, and by a longitude of 124°W there is little or no coupling between the two plates. South of the triple junction, hot mantle material emplaced within the slab window will begin to cool, stiffen, and accrete to the adjacent lithosphere. With sufficient cooling, this material will become effectively welded to the adjacent plates and will translate with them. Thus if one pictures a north-to-south cross section (e.g., along the line of our model in Fig. 1), there is little coupling between the base of North America and the subjacent Gorda plate; however, south of the Gorda plate, a complex pattern of coupling develops between the base of North America and the emplaced slab-window mantle. Mantle material in the slab window will accrete to the exposed (near-vertical) face of the southern edge of Gorda and that material (now pseudo-Gorda) will be in mechanical continuity with mantle accreted to the base of North America south of the triple junction (Fig. 2A). In this way, the migration of the Gorda plate will drive deformation in the overlying North American crust through the viscous coupling within and along the margins of the slab window, producing a basal conveyor belt beneath North America that, because of variations in coupling, preferentially transports material from the south (thinning) to the north (thickening). Since the Mendocino triple junction migrates to the north, this results in first a thickening of crust in advance of the triple junction and then thinning of that thickened crust after triple junction passage.

We have developed a time-dependent (two-dimensional) thermal-mechanical model (Fig. 2) to test the hypothesis that the crustal thickening (and subsequent thinning) observed in the Mendocino region is driven by viscous coupling between the Gorda plate and North America via the mantle material within the slab window. Although the patterns of crustal deformation are three-dimensional (e.g., Fig. 1), available constraints on crustal-thickness variation, patterns of crustal deformation, and plate-boundary geometry in the vicinity of the triple junction do not allow us to constrain and adequately validate a three-dimensional model of the process. The two-dimensional modeling described here is the first step in testing the spatial and temporal consequences of our tectonic hypothesis. The modeling shown in Figure 2 utilized a modified version of the finite element code TECTON (Melosh and Raefsky, 1980; Govers and Wortel, 1995). We specified velocity boundary conditions (Fig. 2A) to simulate the movement of the Gorda plate in the plane of the model. The North American crust could move vertically, but was not allowed to change in total length (implemented by rollers applied to each end of the model at crustal levels) (Fig. 2A). The initial thermal conditions were calculated for the assumed geometry, producing an initial two-dimensional temperature structure for the model consistent with the three-dimensional temperature structure determined by Goes et al. (1997) for the region of the triple junction. The temperature-dependent rheology throughout the model was assumed to be elasto-visco-plastic. Within the limits of the adopted continuum mechanics approach, this assumption allowed us to simulate brittle failure where appropriate in the shallow regions of the crust and visco-elastic deformation throughout the model. Viscosities were assigned, assuming standard temperature-dependent power-law creep for mantle and crustal materials (e.g., Govers and Wortel, 1995).

MODELING RESULTS

We allowed the models to run for between 500 k.y. and 1 m.y. For the given thermal regime, crustal and mantle viscosities, and resulting strain rates, the model reached a dynamic equilibrium after approximately 100 k.y. of Gorda displacement. The model results shown in Figure 2 are a snapshot of the deformation at 300 k.y. (model time). All results after 100 k.y. were equivalent, indicating that viscous spin-up (model initiation effects)

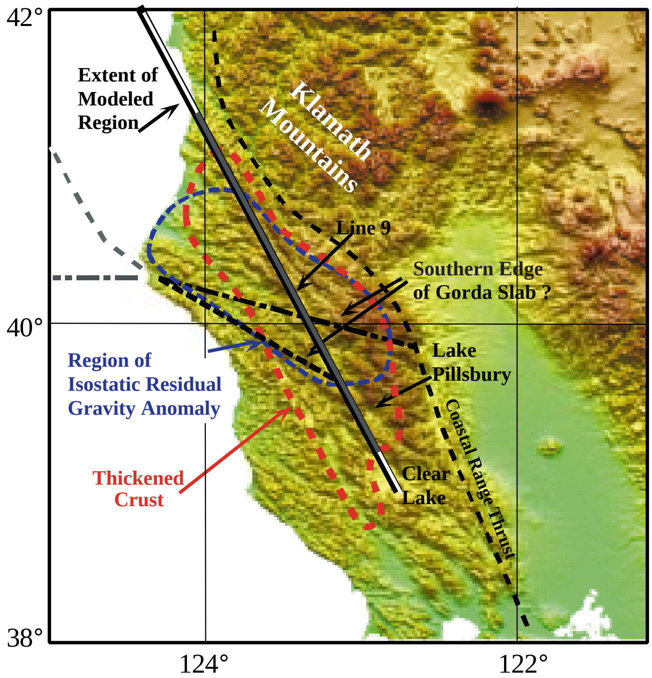

Figure 1. Generalized geophysics of Mendocino triple junction region. Heavy red dashes outline region of observed thickened crust (determined from reflection and wide-angle refraction seismic studies [Beaudoin et al., 1996; Levander et al., 1998; Henstock et al., 1997] and tomography [Verdonck and Zandt, 1994]). Isostatic residual gravity anomaly (light weight, violet dashes) encloses gravity low (~50 mgal) determined by Jachens and Griscom (1983). Extent of region covered by our model (400-km-long profile) is shown by the north-northwest–trending solid line; superposed on that is extent of seismic "Line 9" (250-km-long profile) from Beaudoin et al. (1996). Two previously proposed locations for southern edge of subducting Gorda plate are shown.

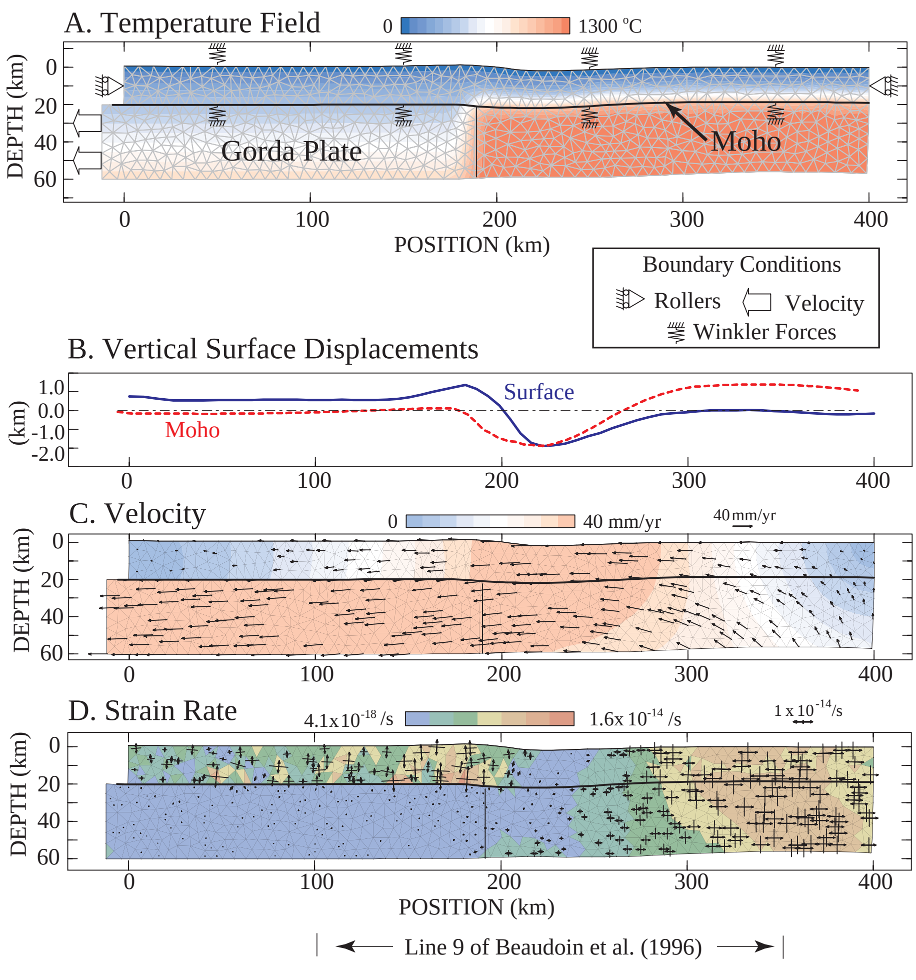

Figure 2. Model configuration and results (at simulated time = 300 k.y.). A: Thermal structure, boundary conditions, and finite-element mesh for model. Applied velocity is 40 mm/yr, rollers allow vertical but not horizontal displacements, and Winkler forces provide gravitational restoring forces to counter effects of displacement of density interfaces. B: Vertical displacement of surface and Moho, relative to initial conditions. C: Resulting velocity field. For clarity, only every third velocity vector is shown. D: Strain-rate field. Color scheme represents magnitude of maximum rate of shear strain, and vectors indicate magnitude and orientation of principal components of strain-rate tensor.

was complete by that time and that the results represent temporally stable deformational processes.

The results shown in Figure 2 are the instantaneous results which delineate regions of crustal thickening, translation, and thinning in association with triple junction passage. Results of the modeling can be utilized in two ways. The model results are directly an instantaneous picture of deformation associated with triple junction passage. Those results can be compared with patterns of crustal deformation such as seismicity, or geodetic observations, and by substituting space for time we can compare them with geologic indicators of deformation south of the triple junction . These instantaneous results can be integrated in space and time (essentially a convolution) to simulate the effects of triple junction migration, producing the pattern of crustal structure variation produced over time. This crustal model can be compared to structural interpretations of the region from seismic and gravity observations.

The results for instantaneous deformation (Fig. 2) are in excellent agreement with observations of deformation and structure in the region. Crustal thickening occurs in the region above the decoupled Gorda plate, driven by the northward displacement of crust from south of the triple junction. The (model-predicted) earthquake activity north of the Mendocino triple junction along this profile would be dominantly the result of shortening within the North American crust, with the base of seismicity above the interface between the North American crust and the underlying (but decoupled) Gorda slab (Figure 2C). In the region extending ~50–75 km south from the southern edge of the Gorda plate, predicted crustal deformation rates are low; in fact, the model results (Figure 2C) show a simple northward translation of a coherent block—compatible with the observed low-seismicity zone (Castillo and Ellsworth, 1993). South of that region, crustal thinning occurs, coincident with the observed seismicity pattern (Castillo and Ellsworth, 1993; Miller and Furlong, 1988).

A maximum crustal thickening rate of nearly 8 mm/yr is predicted just north of the southern edge of the Gorda slab, with average crustal-thickening and crustal-thinning rates of 4-5 mm/yr typical for the deformation zone (Fig. 3). The result of this pattern of deformation is the potential for 20 km or more of thickening (and subsequent thinning) of the North American crust as the triple junction traverses the region (Fig. 3).

Our choice of rheology for the North American crust (Adirondack granulite) produces minimal coupling in the slab-window region. A cooler North American crust and/or more mafic composition for the lower crust would increase this coupling. Models with different levels of coupling between the Gorda plate and North America were also evaluated. Adding coupling along the Gorda subduction interface served to increase the strain in the North American crust and lengthen to the north the region of crustal thickening. The same basic patterns of crustal thickening and thinning were observed in all models.

DISCUSSION AND IMPLICATIONS

An interpretive model of the crustal-structure consequences based on our simulations of Mendocino triple junction passage is compared with results from the reflection and wide-angle refraction seismic experiment (line 9 from Beaudoin et al., 1996) in Figure 4. The pattern of crustal deformation predicted from our modeling is in agreement with observations from the seismic experiment. Observed crustal thickness, determined from both the Mendocino seismic experiment (Beaudoin et al., 1996) and the regional tomographic study (Verdonck and Zandt, 1994), increases from north to south above the Gorda slab in agreement in both location and magnitude with the model predictions. The subsequent crustal thinning south of the triple junction predicted from the model is also consistent with crustal thickness in the region from Beaudoin et al. (1996). Above the subducted Gorda slab, observed seismicity and predicted crustal strain are concentrated in the lower portions of the overlying North American crust. This strain may be responsible for the observed high amplitude reflectivity in the lower crust (Beaudoin et al., 1996) in that area. The lower-crustal reflectivity continues across the low seismicity region (Fig. 4). We interpret that continuation of reflectivity across the region of crustal translation and low deformational strain to be relict from the crustal-thickening deformation which occurred just prior to triple junction arrival. The lower-crustal reflectivity observed in the North American crust above the slab window could also be relict from the crustal-thickening deformational period, but it is more likely produced in situ by the extensional and translational strains associated with post triple-junction deformation.

The location of the proposed lower-crustal melt zone (Fig. 4) near Lake Pillsbury (Beaudoin et al., 1996; Levander et al., 1998) is coincident with the region of predicted maximum crustal thinning (Fig. 2). Although more than 100 km south of the southern edge of Gorda, this is also the site of significant upward flow of mantle material into the slab window. This juxtaposition of extensional strain, a >10-km decrease in crustal thickness, and upwelling flow of mantle material may aid in the development and emplacement of such a melt zone by the combination of pressure-release melting (crustal thinning) and development of a lower-crustal plumbing system (extensional strain). Our modeling results indicate that the location of maximum crustal thinning is relatively stationary over 500 k.y.–1 m.y. periods. This may lead to the development of the discrete volcanic centers which occur within the Coast Ranges. Previous slab-window models of Coast Range volcanism (e.g., Furlong, 1984; Liu and Furlong, 1992) did not explain the development of localized volcanic centers. If such localization also applies to magmatic underplating of the North American crust, a complex pattern of lower crustal structure and composition can be produced.

The model predicted pattern of crustal extension that is superposed after a period of one to two million years on a region of crustal contraction is consistent with the observed geologic history of deformation in the region. In both the Garberville and Round Valley (Covelo) regions of the northern California Coast Ranges (Kelsey and Carver, 1988) inactive contractional thrust faults (e.g., the Dean Creek fault near Garberville) are superseded by active translational

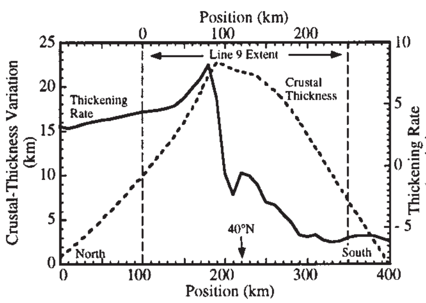

Figure 3. Crustal-thickening rate and resulting crustal-thickness variation (from initial crustal thickness). Two dashed lines delineate extent of line 9 from Beaudoin et al. (1996). Position axes are labeled relative to model dimensions (lower axis) and line 9 positions (upper axis).

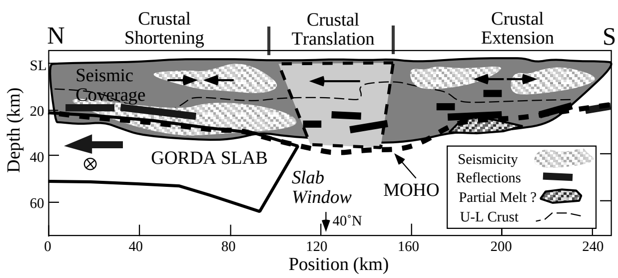

Figure 4. Interpretive cross section along line 9. Shaded region shows extent of crust sampled by reflection and wide-angle refraction experiment (Beaudoin et al., 1996); locations of crustal reflectivity and seismicity are from that study. Position of Moho (bold dashed line) is derived from modeling results of this study (e.g., application of results in Fig. 3). Delineation of deformation regimes (shortening, translation, extension) from Figure 2D. Light dashed line shows boundary between upper and lower crust (U-L Crust).

fault structures (e.g., the Garberville fault) or localized pull aparts (Round Valley).

Published seismicity and seismic structural studies and the modeling results presented here provide a consistent explanation for the location of the southern edge of the Gorda slab, north of and with a more eastward trend than that predicted by the gravity modeling of Jachens and Griscom (1983). Although these data may confirm the location of the southern edge of the subducting Gorda plate, the cause of the significant gravity anomaly astride the Mendocino triple junction region is still unresolved. Our model results provide a surprising explanation for the generation of the gravity anomaly. An unexpected but robust outcome from the modeling is that it shows the development of a flexural downwarp in the crust above and just south of the southern edge of the Gorda plate (Fig. 2B). This elastic flexure is driven by viscous forces acting on the overlying crust developed by flow and strain within the slab window. The feature is dynamic and relaxes if the displacements (i.e., the mantle flow) cease. The model results show ~1.8 km of downwarp (Fig. 2B); if not for this downwarp, elevations straddling the southern edge of the Gorda slab, with the observed crustal thicknesses, would be ~2 km higher than they are. From the perspective of isostatic gravity modeling, this 2 km depression of elevation maps into the equivalent of ~7–10 km of excess (unaccounted for) crust and so could produce the residual anomaly. This wedge-shaped isostatically-hidden crust produces both the magnitude and wavelength of the residual isostatic gravity anomaly seen by Jachens and Griscom (1983). The model results imply that the observed gravity anomaly is a result of the interplay between the crustal-thickening process and flexure driven by viscous forces produced as the Gorda slab migrates.

Uplift and subsidence rates resulting from crustal thickening and thinning, if local isostasy is assumed, are ~0.9 mm/yr and –0.75 mm/yr, respectively. These are minimum estimates since magnitudes could increase if, for example, the Gorda slab provides a strong elastic foundation to the superjacent thickening North American crust. Actual patterns of uplift and subsidence observed in the Coast Ranges will reflect the interaction of this crustal-thickness-driven uplift with the vertical motion produced by the transient flexural downwarp.

There is also a small downward (southward) flexure of the Gorda slab (in the direction of the line 9 profile) as a result of the combination of crustal thickening and the viscous forces described above. This flexure of the Gorda slab, because of differences in elastic thickness, may be expected to have a longer wavelength than that observed in the North American crust. As a result, the flexure may extend north and west of the applied forces and so provide a mechanism to produce the transient subsidence seen in the Eel River basin in advance of the Mendocino triple junction, a setting more typically contractional.

CONCLUSIONS

Although the large-scale plate tectonics of the Mendocino triple junction have been described previously, our understanding of the link between lithospheric-scale processes and regional crustal evolution has been limited. Results of time-dependent, thermal-mechanical finite-element modeling of the consequences of triple junction migration have delineated a suite of processes that ephemerally thicken but permanently deform the North American crust in the vicinity of the triple junction. Magnitudes and spatial patterns of crustal thickening and deformation are in agreement with observed crustal structure, seismicity, and tectonic history as inferred from geologic mapping. The North American crust that has been processed by the Mendocino crustal conveyor is severely modified. The localization of magmatic processes in the wake of the triple junction, the sequence of contraction followed by translation and/or extension at-a-site within the North American plate, the location of mantle upwelling within the slab window, and the development of flexural downwarps are all a consequence of the northward migration of the Mendocino triple junction.

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