Transition from slab to slabless: Results from the 1993 Mendocino triple junction seismic experiment

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ABSTRACT

Three seismic refraction-reflection profiles, part of the Mendocino triple junction seismic experiment, allow us to compare and contrast crust and upper mantle of the North American margin before and after it is modified by passage of the Mendocino triple junction. Upper crustal velocity models reveal an asymmetric Great Valley basin overlying Sierran or ophiolitic rocks at the latitude of Fort Bragg, California, and overlying Sierran or Klamath rocks near Redding, California. In addition, the upper crustal velocity structure indicates that Franciscan rocks underlie the Klamath terrane east of Eureka, California. The Franciscan complex is, on average, laterally homogeneous and is thickest in the triple junction region. North of the triple junction, the Gorda slab can be traced 150 km inboard from the Cascadia subduction zone. South of the triple junction, strong precritical reflections indicate partial melt and/or metamorphic fluids at the base of the crust or in the upper mantle. Breaks in these reflections are correlated with the Maacama and Bartlett Springs faults, suggesting that these faults extend at least to the mantle. We interpret our data to indicate tectonic thickening of the Franciscan complex in response to passage of the Mendocino triple junction and an associated thinning of these rocks south of the triple junction due to assimilation into melt triggered by upwelling asthenosphere. The region of thickened Franciscan complex overlies a zone of increased scattering, intrinsic attenuation, or both, resulting from mechanical mixing of lithologies and/or partial melt beneath the onshore projection of the Mendocino fracture zone. Our data reveal that we have crossed the southern edge of the Gorda slab and that this edge and/or the overlying North American crust may have fragmented because of the change in stress presented by the edge.

INTRODUCTION

The Mendocino triple junction has been affecting the tectonic activity and lithospheric structure of the western margin of North America since its inception 25–29 Ma (Atwater, 1970). As the Juan de Fuca–Pacific plate boundary migrates northward relative to North America, subduction along the Cascadia subduction zone is replaced by the transform boundary of the San Andreas fault system (Fig. 1). The transition from a subduction regime to a transform regime has long been recognized from geologic studies and from upper mantle velocity tomography and potential field studies. How this transition is accommodated on a lithospheric scale, however, is only now being examined with seismic refraction and reflection techniques.

In a rigid-plate model, one consequence of Mendocino triple junction migration is that the North American plate slides off the Gorda plate[1] (a subplate of the Juan de Fuca plate), leaving in its wake a void that is filled by upwelling asthenosphere, often referred to as the slabless window or slab gap (Dickinson and Snyder, 1979; Severinghaus and Atwater, 1990). Supporting evidence for a slabless window exists from heat-flow data (Lachenbruch and Sass, 1970), gravity and magnetic data (Griscom and Jachens, 1989; Jachens and Griscom, 1983), teleseismic P-wave delay studies (Benz et al., 1992; Verdonck and Zandt, 1994; Zandt, 1981; Zandt and Furlong, 1982), shear-wave velocities (Levander and Kovach, 1990), and changes in volcanism (Dickinson and Snyder, 1979; Fox et al., 1985; Furlong, 1984; Johnson and O'Neil, 1984; Zandt and Furlong, 1982). These studies further suggest that (1) the observed upper mantle low-velocity zone is smaller and displaced to the east compared to what would be predicted for rigid-plate models; (2) the Gorda slab is fragmenting along its southern edge; (3) arc volcanism is being replaced by bimodal volcanism that exhibits an age progression northward; and (4) the eastern boundary of the Pacific plate has migrated eastward through a series of jumps of the Mendocino triple junction. Thermomechanical modeling suggests that the boundary at depth between the Pacific and North American plates should step inboard with time as the slabless window cools and new material is accreted to the toe of the Pacific plate (Furlong et al., 1989); recent results suggest that such a process may be occurring in the San Francisco Bay region (Brocher et al., 1994).

In an effort to refine existing models and provide new insights, the Mendocino triple junction seismic experiment (MTJSE) was begun in 1993 (Godfrey et al., 1995; Tréhu et al., 1995). The MTJSE is a multiyear, multiinstitutional effort to study the crust and upper mantle of the North American margin before and after it is modified by passage of the Mendocino triple junction. During August 1993, the first phase of the MTJSE, we collected 650 km of onshore seismic refraction and reflection data to characterize the subduction and transform regimes and the transition between them. This paper presents primary results from this phase of the MTJSE.

GEOLOGIC AND TECTONIC SETTING

Northern coastal California records a history of subduction and accretion that has been active since the Early Cretaceous (Dickinson, 1981). North of the Mendocino triple junction, young (~5 Ma) Gorda plate is subducting obliquely in a northeast direction beneath the North American continent and is deforming the accretionary margin. South of the triple junction, transform mo-

[1] We use the term *Gorda plate* while recognizing that recent work suggests that Gorda deformation zone may be more appropriate (Wilson, 1989).

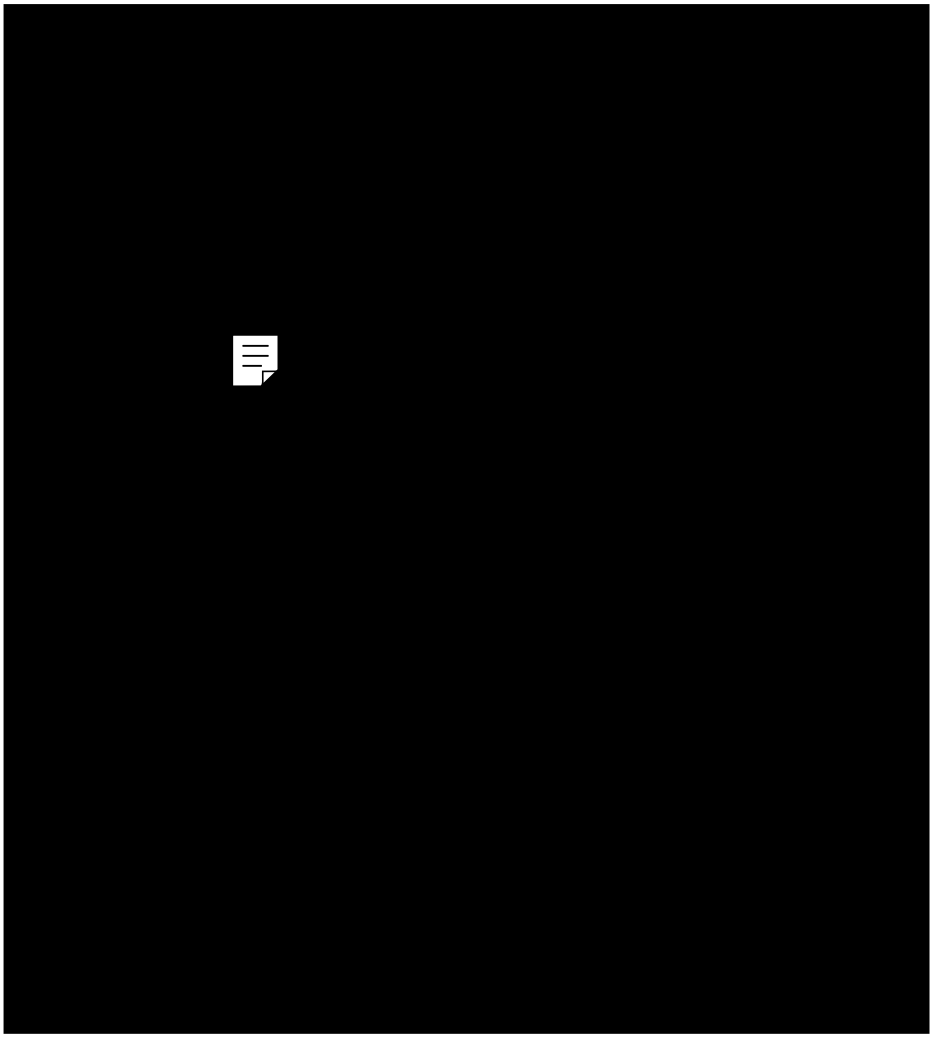


Figure 1. Generalized geologic map of northern California. Squares indicate instrument locations, which commonly overlap to form solid lines. Stars indicate shotpoint locations. BSF is Bartlett Springs fault; CSZ is Cascadia subduction zone; MAF is Maacama fault; MFZ is Mendocino fracture zone; SAF is San Andreas fault; Lk is Lake. Inset shows tectonic setting of Mendocino triple junction seismic experiment. Wiggly lines indicate seismic profiles. Large arrows denote plate motion relative to fixed North America. MTJ is Mendocino triple junction; SEDGE is southern edge of the Gorda slab; GV is Great Valley.

Figure 2. Velocity models for 1993 Mendocino triple junction seismic experiment. Overlain on each model are inferred boundaries (heavy black lines) based on both reflections and regions of high-velocity gradient, approximate maximum depth of direct-arrival ray coverage (dashed line), hypocenters for 1984–1994 from Northern California Seismic Network catalog within 7.5 km of profiles (octagons, hypocenters have errors in depth of ≤2.5 km and lateral position of ≤1.5 km), and regions of high-amplitude reflections from depth-migrated single-fold reflection sections (diagonal ruled pattern; lines 1 and 9 only). A: Line 6 velocity model, which is derived by averaging two independently derived velocity models in region of direct-arrival ray coverage. Beneath this depth, velocity structure was determined from wide-angle reflection modeling. B: Line 1 velocity model, which is derived by averaging four independently derived velocity models in region of direct-arrival ray coverage. Beneath this depth, velocity structure was determined from wide-angle reflection modeling and our 1994 onshore-offshore experiment data. C: Line 9 velocity model. Note that differences in model appearance, sharp lower-crustal velocity boundaries (lines 1 and 6) vs. gradational velocity field (line 9) are due to modeling techniques used.

tion along the San Andreas fault system is shearing the existing continental margin.

The overriding North American plate in the Mendocino triple junction region is an agglomeration of accretionary wedges of the Mesozoic-Cenozoic Franciscan complex (e.g., Blake et al., 1985) overlain by the Eel River basin, a Cenozoic fore-arc basin (Clarke, 1992). The Franciscan complex increases in age and metamorphic grade inboard and is largely composed of metasedimentary rocks. It has been divided into three belts: the Coastal belt, consisting predominantly of a Tertiary accretionary complex; the Central belt, a tectonic melange of Early Jurassic to Tertiary(?) age; and the Eastern belt, Jurassic to Cretaceous blueschist facies rocks (Fig. 1) (Blake et al., 1985). Onshore, the Eel River basin consists of up to 4 km of Miocene and younger sedimentary rocks that lie unconformably on Coastal and Central belt Franciscan complex (Clarke, 1992).

Acting as a backstop for accretion of the Franciscan belts along the Cascadia subduction zone is the Klamath terrane, composed of arc-related rocks of Middle and Late Jurassic age (Harper, 1980). Accretion of the Klamath terrane to the North American margin occurred during the Late Jurassic (Blake and Jayko, 1986). The contact between the Klamath terrane and the Eastern belt Franciscan is thought to be an east-dipping thrust fault.

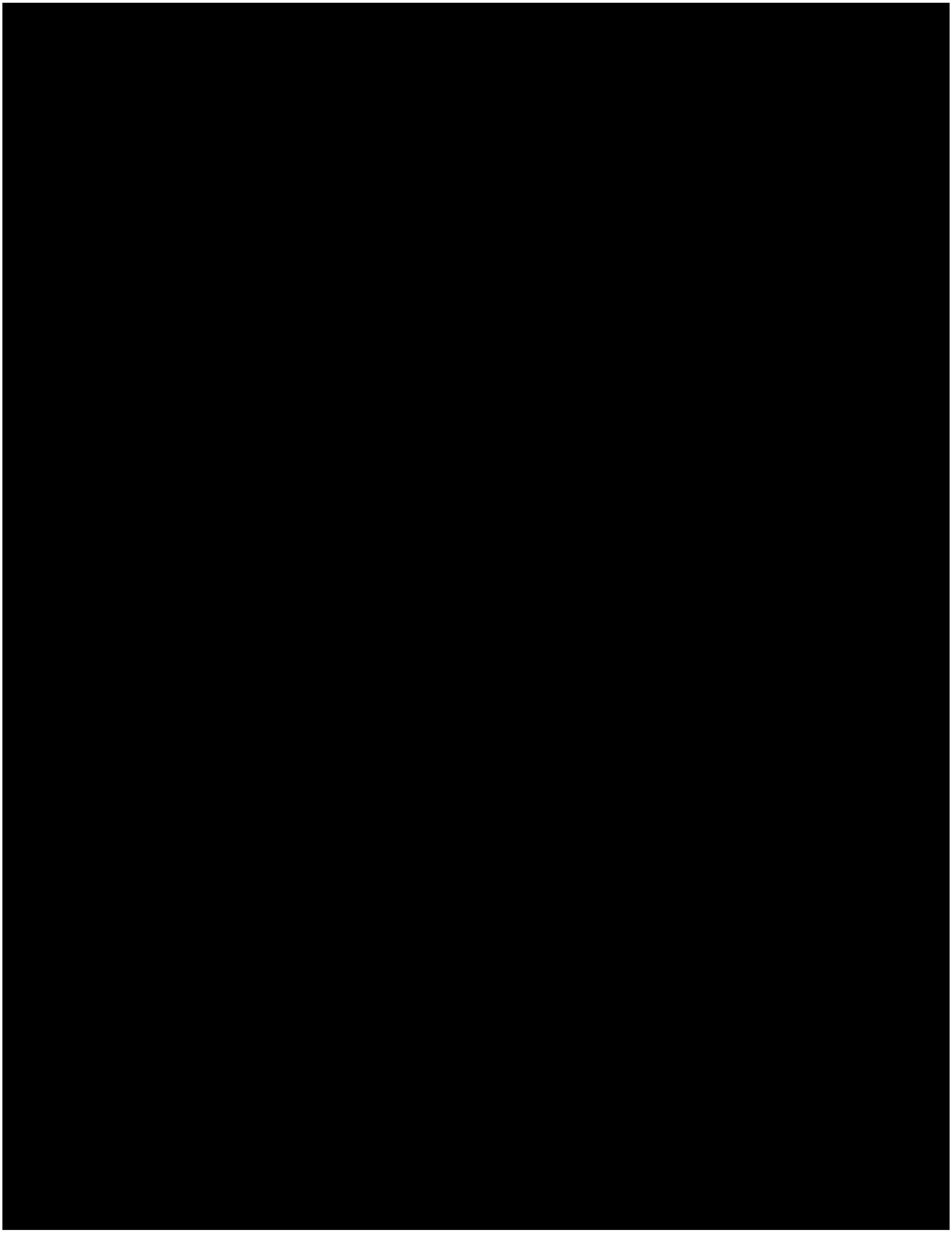
The Great Valley sequence structurally overlies the coeval Franciscan terranes to the west and the Sierran basement to the east; it is composed of a thick section of marine clastic rocks of Late Jurassic to Late Cretaceous age. The fault contact between the Franciscan terranes and the Great Valley sequence is the Coast Range fault.

DISCUSSION

The models presented herein are the result of forward (Luetgert, 1992) and inverse (Hole, 1992; Zelt and Smith, 1992) modeling of traveltimes of both refracted and reflected arrivals. In addition to traveltime modeling, we have incorporated depth-migrated single-fold reflection images into our modeling and interpretations.

Subduction Regime—Line 6

The upper crustal velocity model for line 6 correlates well with observed geology (Fig. 2A). Beneath the western half of line 6, the data indicate that an abrupt transition in upper crustal velocities occurs beneath shotpoint 606 (<5.5 km/s to the west to velocities >6.0 km/s to the east), corresponding to the surface exposure of the Franciscan-Klamath suture (Fig. 2A). A decrease in velocity at a depth of about 10 km beneath the western end of the Klamath terrane suggests that Franciscan rocks are underthrust beneath the Klamaths. On the eastern half of the profile, the Great Valley is shown to be an asymmetric, westward-thickening basin (similar to line 1; see below and Fig. 2) with a maximum thickness of about 2 km. The velocity of the basement beneath the Great Valley is indistinguishable from that of the Klamath terrane.



The base of the crust dips ~11° to the east, as imaged by wide-angle reflections observed from shotpoints 603–606 and 608. A wide-angle reflection observed on 608 and precritical reflections observed on 606 and 607 define a second reflective zone, in the lower crust, that overlies the Moho. The reflectivity of this surface increases considerably to the north (see line 9 discussion). On the basis of correlations with offshore data, seismicity, and crustal structure on a seismic profile along the coast (Beaudoin et al., 1994), we interpret the Moho to represent the base of the Gorda plate crust, and the overlying surface to represent the top of the Gorda plate oceanic crust and/or the North American–Gorda plate boundary. The structure of the lower crust and upper mantle beneath the eastern end of the profile has not yet been determined.

Transform Regime—Line 1

The upper crustal velocity model for line 1 exhibits features similar to those seen in line 6. Great Valley sedimentary rocks are interpreted as a prominent low (<5.0 km/s) in the velocity field, between shotpoints 101 and 104, that defines an asymmetric basin (Fig. 2B). These sediments thicken from east to west, to ~7 km thick beneath shotpoint 103, at which point the depth to basement (defined by velocities >6.0 km/s and observed basement refractions and reflections) becomes poorly resolved, probably because of an abrupt increase in dip. Arrivals from the upper crust, east of shotpoint 105, exhibit clear differences in the velocity structure in crossing from the Great Valley to Franciscan terranes and are modeled as a lateral change in velocity from <5.0 km/s to >5.0 km/s, although the geometry of this boundary has not yet been determined. High-velocity arrivals from just beneath the Great Valley are observed east of shotpoint 104 and are modeled as an increase from 6.0 to 7.0 km/s at the base of ray coverage. These higher velocities could support earlier interpretations of Sierran basement underlying the Great Valley, but they also allow for an ophiolitic basement (Godfrey et al., 1994). The velocity structure west of shotpoint 104, and from orthogonal line 9 (Fig. 2C), suggests that Franciscan rocks exist to at least 18 km depth. The structure at the contact between Franciscan rocks and basement beneath the Great Valley remains enigmatic.

Line 1 exhibits unusually high amplitude reflections from the lower crust and upper mantle in the near-vertical, precritical wavefield (offsets of <30 km) (Fig. 2B). These reflections define three distinct eastward-dipping segments extending from shotpoint 108 to shotpoint 104. The spatial relation between the breaks in these reflectors and the surface and seismic expression of the Maacama and Bartlett springs faults imply that these faults may cut the entire crust. The two subparallel bands of reflections west of the Bartlett Springs fault (roughly midway between shotpoints 105 and 106; Fig. 2B) are interpreted to indicate that either the Pacific plate underlies North American plate as far east as shotpoint 106 (e.g., Benz et al., 1992) or that newly accreted material resulting from the slab window has accreted to the edge of the Pacific plate (e.g., Furlong et al., 1989). At present we cannot distinguish between these two models; however, the extremely high amplitude of the reflections observed beneath shotpoints 106–108 is most likely due to either partial melt or metamorphic fluids. East of the Bartlett Springs fault, the complicated pattern of high-amplitude reflections is interpreted to result from thin layers of partial melt; earlier tomographic results indicate a lower crust–upper mantle low-velocity body north of Clear Lake that was interpreted as an incipient magma chamber (Benz et al., 1992).

From Transform Regime to Subduction Regime—Line 9

Traveltime tomography on line 9 first breaks produces a model of relatively uniform velocity (≤6.3 km/s) crust to depths of ~20 km (Fig. 2C). We interpret this to indicate that Franciscan rocks extend to at least 20 km beneath our profile. At depths greater than 20 km, south to north variations in both the velocity field and model ray penetration are observed. At the southern end, high velocities (>7.0 km/s) occur at 23 km depth. The onset of similar velocities on the northern end defines a southward-dipping zone from 22 km beneath shotpoint 911 to 30 km beneath shotpoint 907.

Reflections from the lower crust and Moho are observed in both the wide-angle and depth-migrated single-fold data (Fig. 2C). The dipping zone of high-velocity material at the north end is coincident with a strong, south-dipping reflector interpreted to be the base of the oceanic crust of the Gorda plate. The high-amplitude reflections above this interface are interpreted as the North American–Gorda plate boundary. This interpretation is consistent with line 6, earthquake hypocenters, and projected depth of slab (cf. Beaudoin et al., 1994). Utilizing both the wide-angle reflection modeling and the depth-migrated single-fold section, we can trace the Gorda slab reflections from shotpoint 911 to just south of shotpoint 907, coincident with the termination of Gorda slab seismicity. At this point we are unable to determine whether the reflectivity beneath shotpoint 906 is associated with the reflective band to the north. The complicated reflector geometry beneath shotpoint 906 may originate from fragments of Gorda slab and/or zones of partial melt. The lower crust–upper mantle reflectivity observed on the southern end of line 9, beneath shotpoints 901–904 and coincident with line 1, is interpreted to originate from partial melt (see above).

Our model for line 9 reveals North American crust that is thickest in the region of the Mendocino triple junction; similar results were reported by Verdonck and Zandt (1994). Though the thickened crust may predate passage of the triple junction and be fortuitously aligned with the slab gap, we interpret this as tectonic thickening of the Franciscan complex in the center of our profile associated with the passage of the triple junction. On the southern end, shallow (~23 km) high velocities suggest thinning of the Franciscan rocks, perhaps due to alteration of the lower crust or assimilation into melt triggered by upwelling asthenosphere (e.g., Johnson and O'Neil, 1984).

We interpret the deep structure beneath line 9 to indicate that the southern edge of the Gorda slab is between shotpoints 905 and 906. Changes in Gorda crust reflectivity and cessation of slab-associated seismicity approaching this edge may be due to either changes in slab continuity or a change in lithologies, and therefore impedance contrast and coupling, across the North American–Gorda plate boundary. Our data do not indicate that the Gorda slab continues as far south as modeled by Jachens and Griscom (1983) (roughly between shotpoints 904 and 905). Rather, south of our interpreted southern edge, a zone of increased scattering and absorption may indicate that fragments of either the Gorda slab or overlying North American plate are left in the wake of the Gorda plate (cf. Benz et al., 1992).

CONCLUSIONS

The MTJSE provides new seismic data that image changes in crustal and uppermost mantle structure associated with the passage of the Mendocino triple junction. Upper crustal velocity models reveal an asymmetric Great Valley basin overlying Sierran or ophiolitic rocks at the latitude of Fort Bragg and overlying Sierran or Klamath rocks near Redding, on average a laterally homogeneous velocity for the Franciscan terranes, and Franciscan rocks underlying the Klamath terrane east of Eureka. Important in our observations and interpretation is the greater thickness of the Franciscan complex in the triple junction region as determined by seismic velocity. We interpret this to indicate tectonic thickening of the Franciscan complex associated with the passage of the triple junction. The thinner Franciscan complex south of the Mendocino triple junction region may indicate assimilation of these rocks into melt triggered by upwelling asthenosphere. The variations in lower crustal reflectors along line 9 and the apparent absorption of seismic energy from the southern shots support a zone of increased scattering, intrinsic attenuation, or both, resulting from mechanical mixing of lithologies and/or partial melt in the central region of line 9 beneath the onshore projection of the Mendocino fracture zone. In the subduction regime, line 6 provides evidence for the existence of the downgoing Gorda slab at least 150 km inboard of the trench. In the transform regime, our data suggest that stalled oceanic crust and/or newly accreted material exists east of the San Andreas fault. Distinct breaks in lower crust–upper mantle reflectors correlate with the Maacama and Bartlett Springs fault, suggesting that these faults cut the entire crust.

The objective of the MTJSE was to image the lithospheric response to Mendocino triple junction passage by comparing and contrasting the subduction regime to the transform regime. Our data reveal that we crossed the southern edge of the Gorda slab and that this edge and/or the overlying North American crust may have fragmented because of the change in stress presented by the edge. Strong indications of partial melt or metamorphic fluids 60–100 km south of this edge exist from both lines 1 and 9 and provide considerably greater detail than earlier tomographic results. In this region of expected slab window, our data indicate the existence of either newly accreted lower crust or tectonically underplated Pacific plate extending as far east as the Bartlett Springs fault. Our data also support the interpretation of thin zones of lower crust–upper mantle partial melt north of Clear Lake. With these results we begin to refine existing models of the Mendocino triple junction region.

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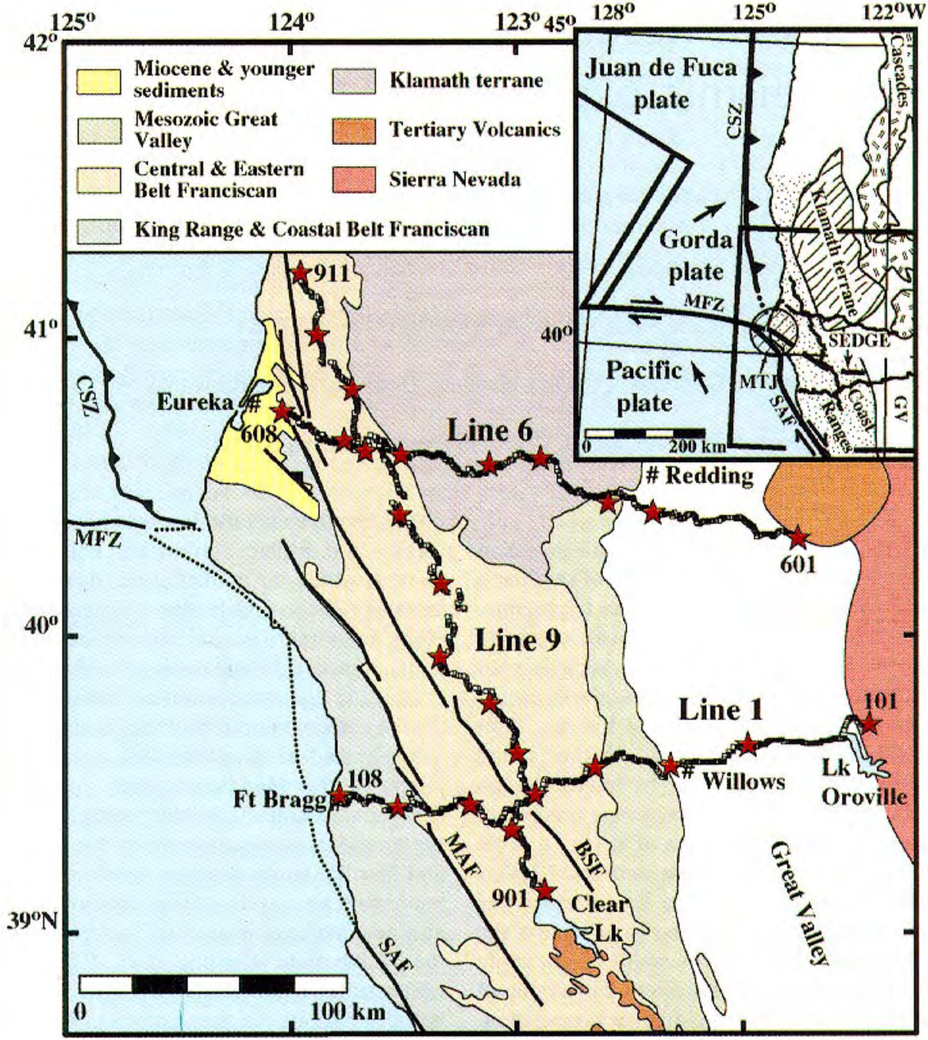

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Gorda plate
Pacific plate
CSZ
MFZ
MTJ
SAF
SEDGE
Klamath terrane
Cascades
Coast Ranges
GV
0
200 km
911
Eureka
608
Line 6
Redding
601
Line 9
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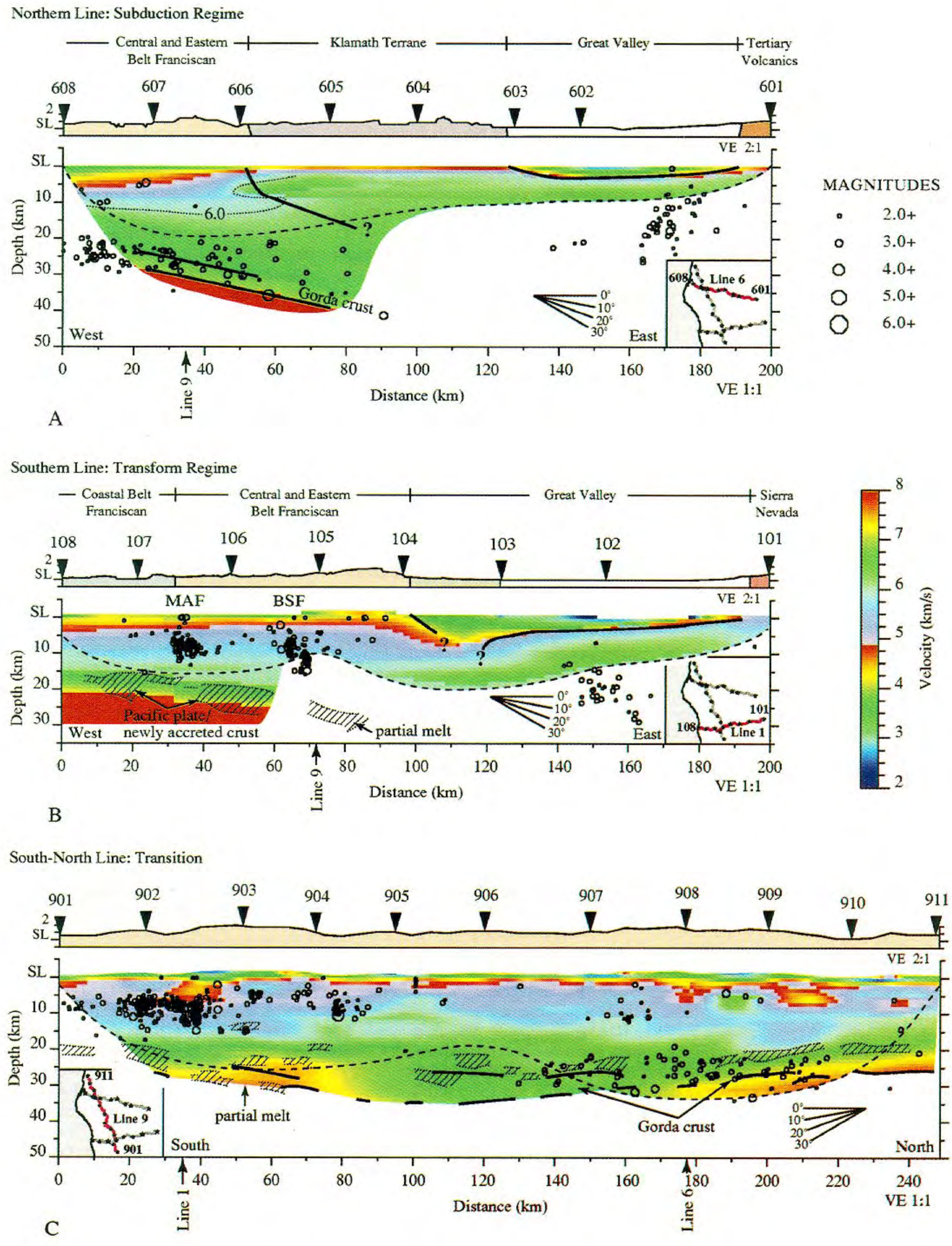
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Southern Line: Transform Regime
Coastal Belt Franciscan
Central and Eastern Belt Franciscan
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