Fluids in the lower crust following Mendocino triple junction migration: Active basaltic intrusion?

Alan Levander
Timothy J. Henstock
Geology and Geophysics Department, Rice University, Houston, Texas 77005
Anne S. Meltzer
Bruce C. Beaudoin*
Department of Earth and Environmental Sciences, Lehigh University, Bethlehem, Pennsylvania 18015-3188
Anne M. Trehu
College of Oceanographic and Atmospheric Sciences, Oregon State University, Corvallis, Oregon 97331-5503
Simon L. Klemperer
Geophysics Department, Stanford University, Stanford, California 94305

ABSTRACT

Geodynamic and plate tectonic models for the Mendocino triple junction, a fault-fault-trench triple junction in northwestern California, predict a slab-free zone south of the triple junction in which asthenospheric mantle upwells to the base of the crust. A variety of geological and geophysical data support this model, although fine-scale (<20 km) details of the lithospheric structure have been unknown previously. Seismic investigations in the onshore transform regime south of the Mendocino triple junction region reveal very strong short-offset reflections from the lower crust and at the crust-mantle boundary beneath the entire width of the Coast Range, particularly near Lake Pillsbury, California. Seismic analysis suggests that these reflections are from discrete zones of fluid. The reflector geometry implies that the source of the fluid is within the upper mantle. In this tectonic context it is likely that the fluids are largely partial melt, segregated from asthenospheric mantle upwelling into the slab-free zone. The tectonic setting and the location of Lake Pillsbury relative to the estimated position of the southern edge of the Gorda slab and the Clear Lake volcanic field suggest that volcanism may initiate in this region within the next 400 k.y.

INTRODUCTION

In northern California, the boundaries of three plates, the Gorda, North American, and Pacific, intersect to form the Mendocino triple junction (Fig. 1). The tectonic evolution of western North America over the past 30 m.y. is intimately linked to the interaction of these three plates (Atwater, 1970), as is modern seismicity and volcanic activity along the western North American margin (Castillo and Ellsworth, 1993). North of the triple junction the Gorda plate is subducting beneath North America. The east-west Mendocino transform fault separates the Pacific and Gorda plates. South of the triple junction, the Pacific and North American plates are in contact across the complex San Andreas transform fault system, which approximately spans the California Coast Ranges. The Mendocino triple junction migrates northward relative to North America through time (McKenzie and Morgan, 1969), with the consequence that the asthenospheric mantle should be emplaced beneath North American terranes south of the Mendocino triple junction, filling space previously occupied by the subducted Gorda plate (Dickinson and Snyder, 1979; Furlong, 1984; Severinghaus and Atwater, 1990). A steady-state geodynamic scenario includes the following. (1) Asthenospheric mantle upwells behind the southern edge of the subducting Gorda plate. (2) The overlying North American crust, composed largely of accreted terranes is heated, uplifted, and intruded by asthenospheric derived melt. (3) Cooling forms new North American lithosphere and results in subsidence along the strike of the transform system. This process is documented by regional heat flow, elevation, geochemical signatures, and low upper mantle seismic velocities (e.g., Atwater, 1970; Zandt and Furlong, 1982; Liu and Furlong, 1992; Benz et al., 1992; Fox et al., 1985).

SEISMIC OBSERVATIONS

The Mendocino triple junction seismic experiment investigated lithospheric structure of subduction, transform, and transition regimes in the triple junction region (Trehu et al., 1995). We describe land seismic data over the presumed asthenospheric window beneath the North American transform margin. Chemical explosions were recorded across the Coast Ranges at lat 39.4°N, with especially dense recordings made near Lake Pillsbury, California (Fig. 1). The seismic data reveal a complicated series of exceptionally bright lower crustal reflections (Figs. 2 and 3). The bright reflections, PiP, occur within an ~5–6-km-thick layer at the base of the crust, which has bulk seismic velocity 6.5–7.0 km/s,

similar in thickness and velocity to oceanic crust (Henstock et al., 1997). The PiP reflections dip east and extend 90 km beneath the North American margin from depths of 16–22 km near the coast to 25–30 km beneath the Coast Range–Great Valley contact (Fig. 2), spanning the area of modern strike-slip faulting.

The reflections vary from being simple single cycle reflections to being complex events with overlapping diffractions (Figs. 2, 3, and 4). PiP reflections start near the boundary between Franciscan terrane rocks and the basal layer (Figs. 2, 3, and 4; Henstock et al., 1997). PiP is consistently large, being comparable to Pg (the direct wave) at offsets of 10–30 km (Fig. 3). A depth migration of a high density single shot gather through an independently derived velocity model shows the detailed structure (Fig. 4). The images show that the bodies causing the reflections extend no more than 2.0–2.5 km laterally and less than 400 m vertically. Although the greatest energy concentration is near the top of the basal layer, the reflections occur throughout the layer to the Moho.

SEISMIC ANALYSIS

We have generated reflectivity synthetic seismograms to investigate the physical properties of the reflecting bodies. Using the one-dimensional seismic velocity model required by the reflectivity

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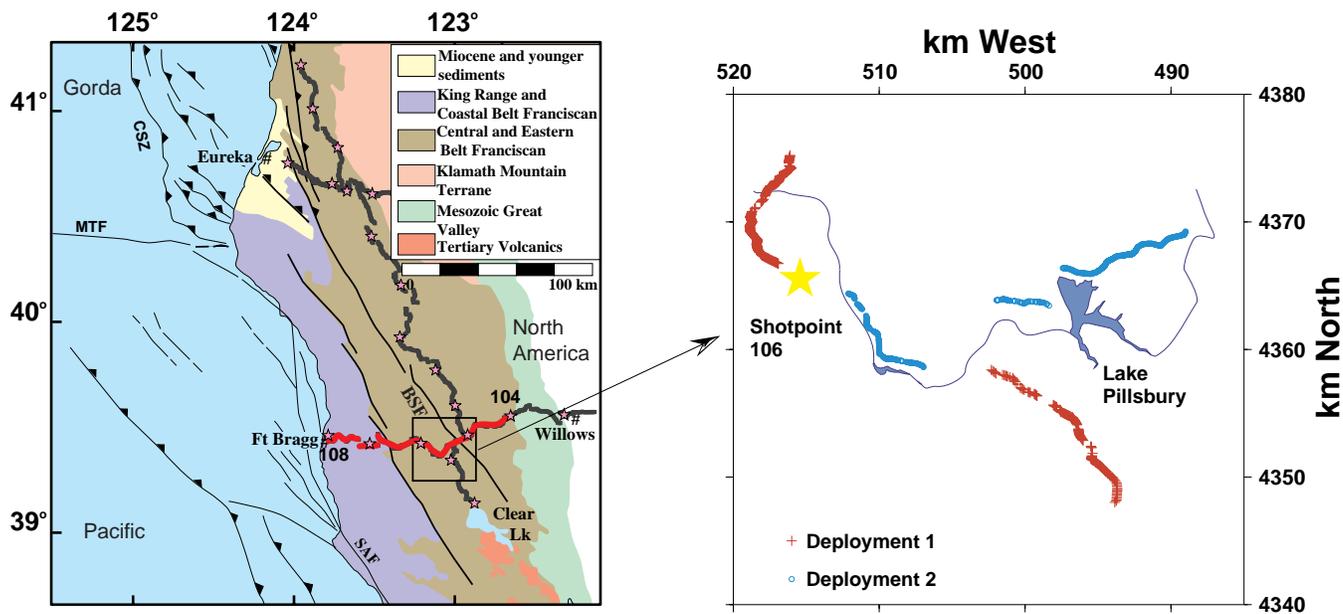
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Figure 1. Mendocino triple junction region location map with shot locations, and low-density receiver array. Inset: Lake Pillsbury high-density receiver arrays near shotpoint (SP) 106. CSZ—Cascadia subduction zone, MTF—Mendocino transform fault, SAF—San Andreas fault, BSF—Barlett Springs fault.

method means that we underestimate seismic velocity and density variations when matching the data. The local dip at the target zone is inadequate to significantly influence the results. Our wide-angle velocity model was refined to match the amplitude variation with offset (AVO) of the direct arrival (Pg) recorded in our high density array. We then calculated the ratio of the PiP amplitude to Pg at offsets of 0–30 km, and compared these to the synthetic predictions. The Pg normalization accounts for different recording site responses in the field data. Although there is scatter in these ratios, there is a high degree of consistency in the AVO response independent of the shots or recording instruments (Fig. 3). At offsets of 10–30 km, the reflections are as strong as the Pg arrival, requiring an absolute reflection coefficient of 0.3, three times greater than a large crustal reflection coefficient. We have investigated seis-

mic shot records with offsets of as much as 90 km and concluded that the high amplitude is not a critical angle effect from a simple interface, because one would not expect a post-critical reflection from a depth of 20 km until offsets of ~80 km given the bulk velocity contrasts in the lower crust (Henstock et al., 1997). Moreover, the reflections have similar spectra to the Pg phases; assuming that Pg has the seismic source spectra, this precludes any widespread tuned amplitude enhancement in the target zone. The broad region (90 km wide) over which we observe high amplitudes implies that the reflections are not simply due to localized focusing of energy.

The PiP/Pg ratios from a variety of synthetic models are plotted in Figure 3. The AVO response can be reproduced by a discrete thin layer with low compressional and shear velocities (3.5 km/s and < 1.0 km/s, respectively), or high velocities

$(Vp \cong 9$ km/s). The latter is unlikely for any crust or upper mantle lithology. We prefer the low-velocity interpretation for a number of reasons. Where the onset of the reflections can be clearly seen, the polarity appears opposite to that of the first break on the same trace, implying a negative reflection coefficient (Fig. 3). The polarity response is not unique because of interference between primary reflections from the short bodies, and diffractions from their ends. We also prefer the low-velocity interpretation because our high-density recording shows a weak phase on the vertical component motion with traveltime, phase velocity, and amplitude consistent with a converted S-wave predicted by the low-velocity zone reflectivity modeling (Fig. 3).

We have also analyzed the Moho reflection PmP. The amplitude of PmP divides geographically into two distinct fields. Beneath the western side of the Coast Ranges, the amplitudes in the offset range 0–30 km are consistent with those expected from our regional velocity model, but amplitudes from the east are significantly higher. The high PmP amplitudes can be matched with a thin low velocity layer at the Moho. The zone of enhanced Moho reflectivity lies directly above the region of lowest mantle P-wave velocities in seismic tomography results (Benz et al., 1992; Benz, 1997, personal commun.).

INTERPRETATION

The observations suggest that the bright reflections result from relatively small discrete bodies with high concentrations of fluids, either aqueous or melt. The presence of the reflectors throughout the lower crust to the Moho implies that a lowermost crust or mantle source is more likely than an accretionary complex source for the fluids,
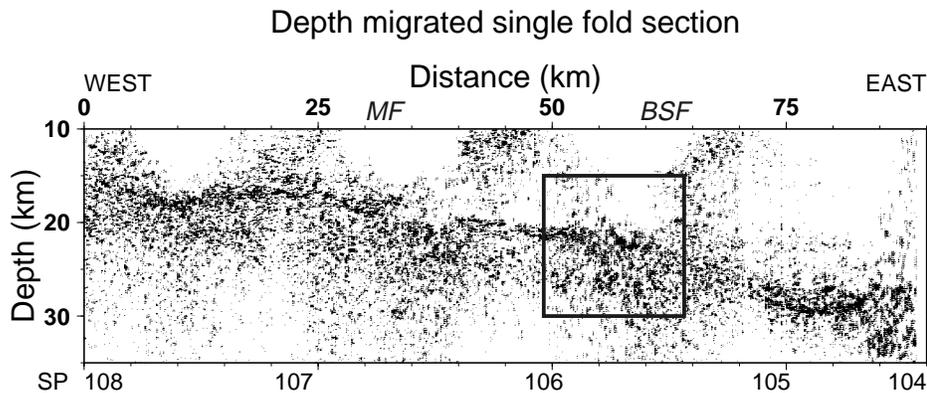
Depth migrated single fold section

Figure 2. Depth migrated single fold section from shots 104–108, shown as energy plot. Bright reflections appear beneath all shotpoints. To west, beneath shotpoints (SP) 106 and 107, the reflections appear as two discrete bands. Beneath SP 105 reflections appear as thick zone. High-density profiles measured reflections near SP 106. Extent of the image in Figure 4 is shown in gray box. MF—Macaama fault, BSF—Bartlett Springs fault.
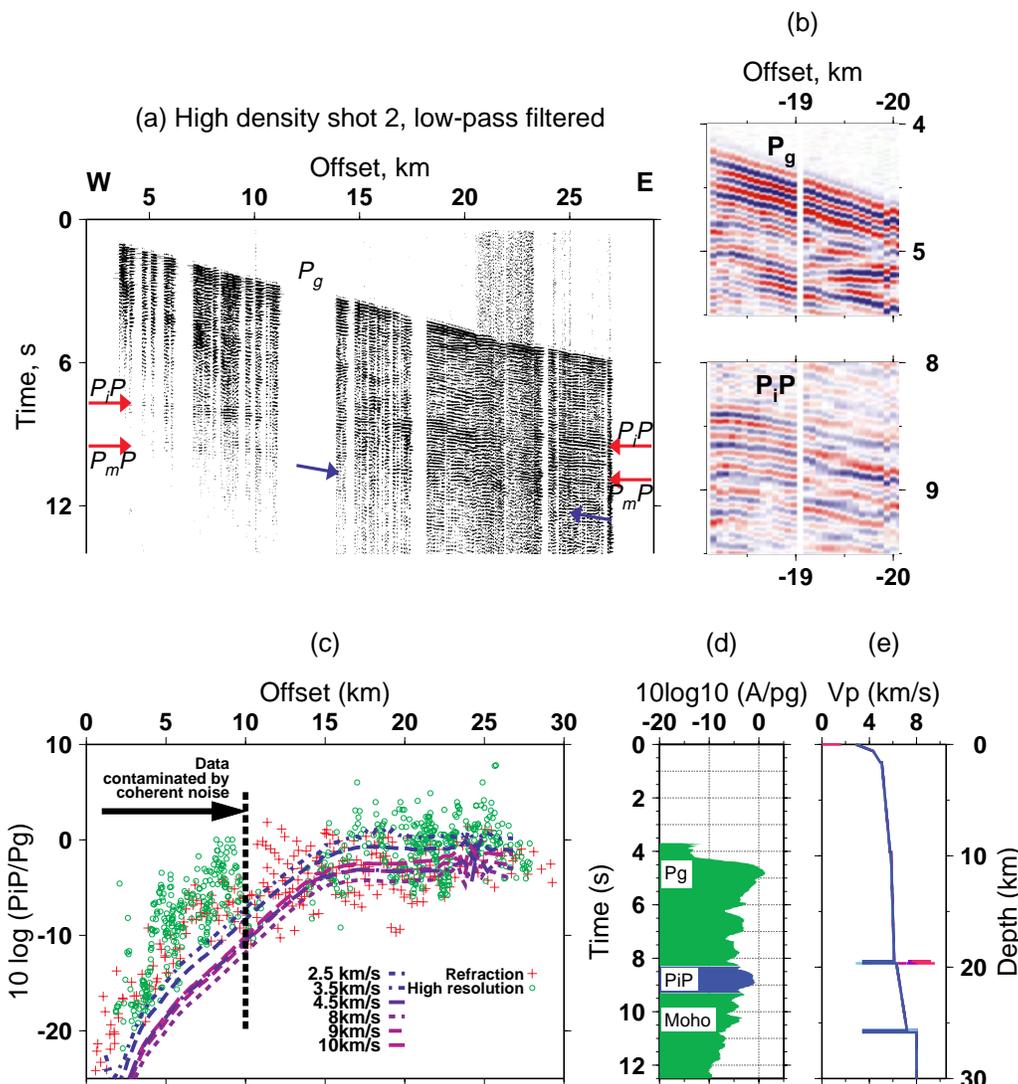
(b)
Offset, km

(a) High density shot 2, low-pass filtered

(c)

(d)

(e)

Figure 3. (a) High density recordings at SP 106 showing Pg, PiP, PmP, and a converted shear wave (blue arrows), (b) comparison of polarity between Pg and PiP, (c) amplitude versus offset response, (d) representative amplitude decay curve, and (e) one-dimensional velocity model. Amplitude decay curve is averaged over several traces. The preferred seismic velocity model is shown in blue, an alternate high velocity model is shown in red. We cannot resolve changes in layer thickness from 100 to 400 m.

because the latter would require fluids to migrate downward. To interpret the nature of the fluids, we examine the tectonic setting in more detail.

The regional morphology of the bright reflections beneath the North American margin (Fig. 3) is consistent with either subducted oceanic crust, as inferred elsewhere in the California transform margin (e.g., Brocher et al., 1994; Lafond and Levander, 1995, and references therein), or with predictions of models for an asthenospheric window (Furlong, 1984; Zandt and Furlong, 1982). In either case we link these reflections to the passage of the Mendocino triple junction at 2–3 Ma, because (1) only very weak normal incidence reflections are seen in marine reflection data at equivalent depths beneath the Pacific plate west of the San Andreas fault (Henstock et al., 1997). (2) The basal layer seen farther south beneath the California margin does not show equivalent high amplitude reflections. (3) AVO analysis of reflections from the subducting Gorda plate north of the triple junction shows amplitudes a factor of three smaller.

We suggest that the reflections result from a complex system of basalt melt sills generated

from upwelling asthenosphere following triple junction migration (Furlong, 1984), although they might arise from layers of aqueous fluids resulting from subduction and/or dehydration reactions (Watson and Brenan, 1987; Calvert and

Clowes, 1990; Shipley et al., 1994). The seismic data alone do not differentiate between the two possibilities, forcing us to rely on circumstantial evidence. It is unlikely the fluids are inherited from the subduction system: (1) The residence
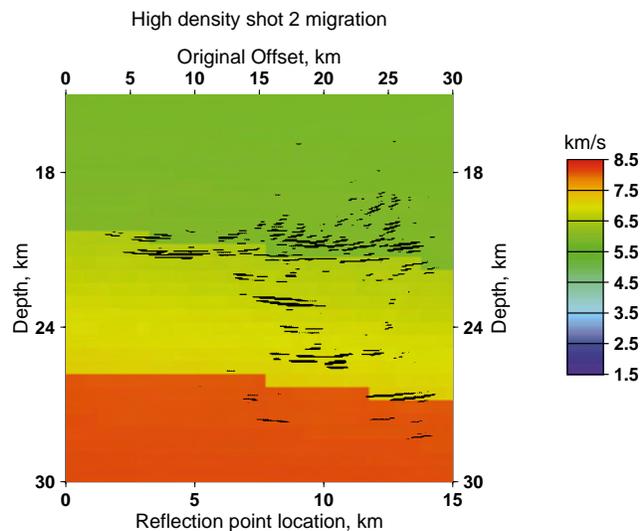

High density shot 2 migration

Figure 4. Migrated shot gather from the high-density study near Lake Pillsbury (Fig. 1). Background velocity field was determined from inversion of refraction traveltimes. Top horizontal scale shows source to receiver offset (compare to Fig. 3a). Bottom horizontal scale shows migrated reflector position (compare to box in Fig. 2). Reflections cluster near top of basal layer, and are distributed throughout it. Lateral extent of reflecting bodies is <2.5 km; likely an overestimate due to limitations of single shot gather migration.

time for water in the lower crust in noncompressive settings is short (Bailey, 1990). (2) Dehydration of oceanic crust in the Cascadia subduction zone occurs in ~0.5 m.y. (Hyndman, 1988), and these fluids are expelled rapidly (<1.0 m.y.) when the subduction-related compressive stress field changes (Goldfarb et al., 1991). (3) Equally bright reflections are not seen in the subduction regime north of the Mendocino triple junction, where such fluids might be expected. Arguments supporting the melt hypothesis are as follows: (1) The reflections in the transform regime are similar to reflections from thin magma bodies in Death Valley and the Rio Grande Rift (de Voogd et al., 1986), but larger than the subduction zone reflections attributed to aqueous fluids beneath Vancouver Island (Hyndman, 1988; Calvert and Clowes, 1990). (2) The reflection geometry suggests a mantle source, which would require dehydration reactions as well as basalt generation in the uppermost mantle. (3) A series of bimodal volcanic fields with mantle melt signatures in the Coast Ranges show a correlation between the passage of the triple junction and the onset of volcanism across 600 km during the last 20 m.y. (Fox et al., 1985).

The northward-younging 2 Ma to ca. 10 ka Clear Lake volcanic field (Fox et al, 1985; Donelly-Nolan et al., 1981) is the most recent surface expression of this volcanism. Clear Lake and Lake Pillsbury are both actively extending pull-apart basins, thus the local tectonic setting and the location of Lake Pillsbury are appropriate for a locus of future volcanism. The southern edge of the Gorda slab, which marks the northern boundary of mantle upwelling, is 40–50 km north of Lake Pillsbury (Beaudoin, personal commun., 1997; Jachens and Griscom, 1983). The Lake Pillsbury basin is ~75 km from the initial volcanism at Clear Lake. Using a migration rate for the Mendocino triple junction of 30–40 mm/yr (Argus and Gordon, 1991), one can predict volcanic activity that exactly keeps track with the Mendocino triple junction would occur in the Lake Pillsbury region within the next 400 k.y. (150 ± 250 k.y.).

The upper reflection is at the top of the basal layer which has velocities typical of mafic lithologies, while the deeper reflections are at the level of Moho formation. This is similar to the midocean ridges where melt due to upwelling asthenosphere is found in discrete bodies, both shallow and near the oceanic Moho (Kent et al., 1993; Garmany, 1989). Because a 100 m thick sill solidifies in ~1000 yr., melt generation must be ongoing. Discrete magma chamber reflections have been reported in broad regions of extension where upwelling asthenosphere decompresses and melts, whereas this tectonic setting is mostly transpressive. Asthenospheric upwelling here results from removal of a subducted slab, a process which occurred for much of the California margin since 29 Ma.

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