Evolution of the Gorda Escarpment, San Andreas fault and Mendocino triple junction from multichannel seismic data collected across the northern Vizcaino block, offshore northern California

Nicola J. Godfrey¹,², Anne S. Meltzer³, Simon L. Klemperer¹, Anne M. Tréhu⁴, Beate Leitner⁴,⁵, Samuel H. Clarke, Jr⁶ and Amy Ondrus³

Abstract. The Gorda Escarpment is a north facing scarp immediately south of the Mendocino transform fault (the Gorda/Juan de Fuca-Pacific plate boundary) between 126ºW and the Mendocino triple junction. It elevates the seafloor at the northern edge of the Vizcaino block, part of the Pacific plate, ~1.5 km above the seafloor of the Gorda/Juan de Fuca plate to the north. Stratigraphy interpreted from multichannel seismic data across and close to the Gorda Escarpment suggests that the escarpment is a relatively recent pop-up feature caused by north-south compression across the plate boundary. Close to 126ºW, the Vizcaino block acoustic basement shallows and is overlain by sediments that thin north toward the Gorda Escarpment. These sediments are tilted south and truncated at the seafloor. By contrast, in a localized region at the eastern end of the Gorda Escarpment, close to the Mendocino triple junction, the top of acoustic basement dips north and is overlain by a 2-km-thick wedge of pre-11 Ma sedimentary rocks that thickens north, toward the Gorda Escarpment. This wedge of sediments is restricted to the northeast corner of the Vizcaino block. Unless the wedge of sediments was a preexisting feature on the Vizcaino block before it was transferred from the North American to the Pacific plate, the strong spatial correlation between the sedimentary wedge and the triple junction suggests the entire Vizcaino block, with the San Andreas at its eastern boundary, has been part of the Pacific plate since significantly before 11 Ma.

1. Introduction

Three plate boundaries intersect at the Mendocino triple junction (Figure 1a, inset). The Gorda/Juan de Fuca plate is subducting beneath the North American plate along the Cascadia subduction zone. The San Andreas fault is a right-lateral strike-slip fault separating the Pacific plate from the North American plate. The Mendocino transform fault is a right-lateral transform fault separating the subducting Gorda/Juan de Fuca plate and the Pacific plate. There is a topographic high immediately south of the Mendocino transform fault between 129ºW and the Mendocino triple junction [Krause et al., 1964; Silver, 1971]. Between 129ºW and 126ºW this topographic high is a ridge, the Mendocino Ridge, which separates bathymetrically lower (older) Pacific plate to the south from bathymetrically elevated (young) Gorda plate to the north. Between 126ºW and the Mendocino triple junction, in addition to the topographic high of the Mendocino Ridge, there is the Gorda Escarpment, a north facing scarp which forms the northern edge of the Vizcaino block, part of the Pacific plate (Figure 1a). The Vizcaino block is bounded on the east by the San Andreas fault and on the southwest by a break in continental slope (Figure 1a) interpreted as a paleosubduction trench [McCulloch, 1987a]. The Vizcaino block is an anomalously broad, triangular part of the continental slope that is believed to consist of accretionary prism material overlying oceanic crust stalled in a fossil subduction zone [McLaughlin et al., 1994].

We expect a particular bathymetric relationship across the Mendocino fracture zone based on the age of the lithosphere on either side of the plate boundary; young, elevated Gorda plate to the north versus old bathymetrically low Pacific plate to the south [Engebretson et al., 1985]. West of 126ºW, the bathymetry north and south of the Mendocino transform fault and Mendocino Ridge is as expected (see profiles 4 - 12 in Figure 3 of Krause et al. [1964]). East of 126ºW, the bathymetric relationship is also as expected, except within 15 km south of the Mendocino fault, i.e., within the Vizcaino block. Within the Vizcaino block, the bathymetry shallows significantly as the Mendocino transform fault is approached (see profiles 1-3 in Figure 3 of Krause et al. [1964]) culminating in the bathymetrically high Mendocino Ridge adjacent to the steep north facing scarp, the Gorda Escarpment [Krause et al., 1964].
This paper uses three multichannel seismic data sets and gravity data recorded across the Gorda Escarpment and northern part of the Vizcaino block to investigate the evolution of the Gorda Escarpment and to try and constrain when the present Mendocino triple junction-San Andreas fault-Mendocino fracture zone geometry was established.

1.1. Tectonic Setting

The Mendocino (fault-fault-trench) triple junction and Rivera (fault-ridge-trench) triple junction formed at ~29-30 Ma, at about 31° N (in a modern fixed-North America reference frame), when the Pacific-Farallon spreading ridge intersected the subduction zone along the North American margin [Atwater, 1970; Stock and Molnar, 1988]. The Mendocino triple junction has been associated with the Mendocino fracture zone since at least 27 Ma [Stock and Molnar, 1988] and both have migrated northwest (relative to fixed North America) to their present locations at about 40.5° N (Figure 1a). The Rivera triple junction has, during the same period of time, migrated south (with respect to fixed North America) by a series of jumps to about 23° N, off the west coast of Mexico. As the triple junctions migrate away from one another, the San Andreas transform system lengthens, progressively changing the subduction regime to a transform setting [Atwater, 1970]. The transform margin in northern California is not a simple plate boundary. Current motion on the northernmost San Andreas fault system appears to be distributed across at least three major faults over a 50-km-wide region. The San Andreas fault is the westernmost active fault [Castillo and Ellsworth, 1993]. Late 20th century seismicity, however, is restricted to the Ma'acama and Bartlett Springs faults which lie east of the San Andreas fault [Castillo and Ellsworth, 1993]. Geodetic models also suggest that most of the strike-slip motion along the plate boundary is currently accommodated on these easternmost faults (J. T. Freymueller et al., Kinematics for the Pacific-North America plate boundary zone, northern California, submitted to Journal of Geophysical Research, 1998).

The Mendocino triple junction is a broad zone of deformation presently centered near the town of Petrolia, onshore Cape Mendocino [Clarke, 1992] (Figure 1a, inset). It is not a simple point in space but rather a region where the North American, Gorda, and Pacific plates interact. It is associated with an anomalously elevated region [Aalto et al., 1995] with unusually high uplift rates [Merrits and Vincent, 1989].

From about 33 to 8 Ma (chrons 13 to 4), the direction of motion of the Pacific plate was N60°W with respect to the North American plate [Stock and Atwater, 1997; J. M. Stock and T. Atwater, Pacific-North America plate tectonics of the Neogene southwestern United States- An update, submitted to International Geological Review, 1998]. From about 30 to 12 Ma, the Pacific plate velocity with respect to the North American plate was about 33 mm/yr and from 12 to 8 Ma, it was about 52 mm/yr (J. M. Stock and T. Atwater, Pacific-North America plate tectonics of the Neogene southwestern United States- An update, submitted to International Geological Review, 1998). At about 8 Ma, the relative motion between the Pacific and North American plates changed to N37°W, although the plate velocity remained 52 mm/yr [Stock and Atwater, 1997; J. M. Stock and T. Atwater, Pacific-North America plate tectonics of the Neogene southwestern United States- An update, submitted to International Geological Review, 1998]. At about 3.5 Ma, the relative motion changed to north-northwest [Harbert and Cox, 1989]. The Farallon and later the Juan de Fuca/Gorda plates moved east with respect to the North American plate (parallel to the Mendocino fracture zone) [Wilson et al.,
...been at sea level and has since subsided [Krause et al., 1964]. The ages (11-22 Ma) of these samples from the Mendocino Ridge [Krause et al., 1964; Duncan et al., 1994; Fisk et al., 1996; Krause et al., 1997]. Rounded cobbles and gravels from the ridge indicate that the escarpment must once have accreted prism material, comparable to the onshore Franciscan complex, overlying stalled, partially subducted oceanic crust or underplated mafic material [Bachman et al., 1984; McLaughlin et al., 1994; Henstock et al., 1996, 1997].

North of the Mendocino Ridge/Gorda Escarpment is the Juan de Fuca/Gorda oceanic plate. For the remainder of this paper we simply refer to the Juan de Fuca/Gorda plate as the Gorda plate, although we recognize that the "Gorda plate" is a broad deformation zone associated with the southernmost Juan de Fuca plate [Wilson, 1986, 1989]. The Gorda plate is overlain by accretionary prism material associated with the Cascadia subduction zone [Gulick et al., 1998] which in turn is overlain by the sedimentary section of the Eel River forearc basin [Clarke, 1992] (Figure 1a). The Eel River basin contains, from its base upward, remnants of a Lower Cretaceous clastic sequence, remnants of a lower and middle Eocene marine sequence, a marine clastic Miocene section, and Pliocene sandstones and siltstones [Hoskins and Griffiths, 1971; Clarke, 1992]. Young folds and thrust faults (mostly post-Pliocene) trend north throughout most of the basin, indicating recent (post-Pliocene) east-west compression associated with the Cascadia subduction zone [Clarke, 1987, 1992]. In the southernmost part of the basin, the young folds and thrust faults trend northwest reflecting northeast-southwest compression. The rotation of faults and folds to a more east-west trend in the southernmost part of the Eel River basin and seismicity concentrated in the southern part of the Gorda plate on some of these faults [Smith et al., 1993] suggests a present-day component of north-south compression close to the Mendocino transform fault and triple junction [Ogle, 1981; Stoddard, 1987; Clarke, 1992]. Recent strike-slip faults have also been mapped in the offshore Eel River basin [Gulick et al., 1997].

2. Data

Our results are based on three seismic data sets and gravity data.

2.1. New Seismic Data

In 1994, during the Mendocino Triple Junction Seismic Experiment (MTJSE), we collected marine multichannel seismic reflection (MCS) data [Tréhu et al., 1995] in the...
both seismic lines and the andesite recovered from the base of the basement ridge making up the basement high known as the Oconostota ridge (open circle, Figures 1a and 1b) [Shipboard Scientific Party, 1997]. It was drilled at the western margin of the Point Arena basin and bottomed in early Pliocene-late Miocene (?) sediments at 387.7 m below sea floor [Shipboard Scientific Party, 1997]. It does not intersect any of the seismic lines interpreted in this paper. The site survey seismic data for ODP Site 1022 intersects the south end of line 5 on the southwestern side of the Oconostota ridge, making correlation of horizons farther north along line 5, northeast of the Oconostota ridge, very difficult.

Three other wells in the southernmost part of the basin were drilled for hydrocarbon exploration (small solid circles, Figure 1a). Industry data with relatively dense coverage close to the coast have been correlated with these wells, allowing the mapping of dated unconformities, which are imaged as distinct horizons in the MCS data, from the south of the basin to the eastern part of the Gorda Escarpment [Ondrus, 1997; A. S. Meltzer et al., manuscript in preparation, 1998]. The Point Arena Formation (or its time correlative equivalent) is the oldest sequence that can definitively be mapped from the south to the northern part of the basin. The unconformity associated with this formation corresponds approximately to the base of upper Miocene (about 11 Ma [Harland et al., 1982]). The unconformity is a bright, distinctive reflector on lines 25 (Figures 1 and 2) and A (Figures 1 and 3). We infer the position of the base-of-upper-Miocene reflector on lines 7 and B (Figures 1 and 4) by comparing the character of the reflections on lines A, 7, and B.

2.4. Gravity Data

Gravity data were collected aboard the R/V Maurice Ewing in 1994 along the same transects as the MCS lines. The data were collected using a Bodenseewerke KSS-50 marine gravity meter, which logged data at 6-s intervals. The data were corrected for drift, and an Eötvos correction and DC shift were applied to obtain the free-air anomaly at 1-min time intervals. Models derived from the shipboard gravity data along lines A, B, and C were used to constrain the interpretation of the seismic data. The models were derived from the gravity data along the north-south transects, and the seismic data were used to refine the models in the east-west direction.

2.3. Age Constraints Within the Point Arena Basin

There are few wells in the Point Arena basin to aid the assignment of ages to horizons imaged in the MCS data: two deep drill hole sites in the northwestern part of the Vizcaino block (Deep Sea Drilling Project (DSDP) Site 173 and Ocean Drilling Program (ODP) Site 1022) and three hydrocarbon exploration wells in the southernmost part of the Vizcaino block (Figure 1a, circles). The hole at DSDP Site 173 was drilled on the westernmost basement ridge making up the basement high known as the Oconostota ridge (open circle, Figures 1a and 1b) and is therefore just beyond the western margin of the Point Arena basin. The hole at DSDP Site 173 bottomed in undated submarine andesitic volcanic breccia overlain by upper Oligocene/lower Miocene (?) marine nanofossil ooze [Shipboard Scientific Party, 1973]. MCS lines 4 and 5 cross the DSDP drill site (open circle, Figures 1a and 1b), and there appears to be good correlation between a bright reflection on both seismic lines and the andesite recovered from the base of the hole [Leitner et al., this issue, Figure 4]. This horizon is not suitable for regional correlation since it pinches out against the other basement ridges that make up the Oconostota ridge.

A more recent deep hole drilled at ODP Site 1022 was drilled 16 km northeast of DSDP Site 173 (gray circle, Figures 1a and 1b) [Shipboard Scientific Party, 1997]. It was drilled at the

Figure 2. Migrated, depth-converted sections of line 25. (a) True-scale section. Tick marks correspond to those on map (Figure 1b). (b) Section with vertical exaggeration of 4, and (c) line drawing.
3. Observations

3.1. Western Gorda Escarpment

Lines 5 (Figure 6), 32 (Figure 6), and 33 cross the Gorda Escarpment in the western part of the Vizcaino block (Figure 7, and B provide information about basement and basin structure in regions where there are no coherent reflections on the MCS data due to complex seafloor topography. Figure 5 shows the gravity data along lines A, 7, and B, along with the preferred models. Gravity models along lines 3S, 4, and 5 (Figure 1a) are presented by Leitner et al. [this issue].
The dated horizons from the hole at DSDP Site 173 (which intersects the southern end of line 5) that can be correlated with reflectors in the seismic data [Leitner et al., this issue, Figure 4] cannot be traced north along line 5 with any certainty because the horizons are disrupted by the Oconostota ridge (Figure 1). Figure 6 shows the sedimentary section overlying the northwestern Vizcaino block has a maximum thickness of about 1.5 km. The acoustic basement shallows to the north toward the Gorda Escarpment, with the overlying sediments thinning as they approach the top of the ridge (Figure 6). Acoustic basement is exposed at the seafloor at the ridge crest (Figure 6). The most recent sediments are tilted south and are eroded at the seafloor (Figure 6). The tilted sediments are restricted to within about 20 km of the ridge crest and imply relatively recent uplift of the ridge. Rounded cobbles dredged from the ridge crest [Krause et al., 1964; Fisk et al., 1993] imply the ridge was once at sea level and has since subsided, because the ridge is now 1.5 km below sea level. West of 126°W, the crest of the Mendocino Ridge and Gorda Escarpment were above sea level at about 5-6 Ma [Fisk et al., 1996]. If this is also true east of 126°W, it implies that the pop-up of the escarpment occurred sometime prior to 5-6 Ma, and then the ridge subsided to its present depth.

3.2. Triple Junction Region

Lines A (Figure 3), 7 (Figure 4) and B (Figure 4), and several industry lines cross the Gorda Escarpment and northeasternmost part of the Vizcaino block (Figure 1). These lines show the 1-4-km-thick Point Arena basin sedimentary section and a prominent reflection at 2.5-5 km depth that is the top of acoustic basement (Figures 3 and 4). A deeper reflection (6.8-8 s twtt) is also imaged on lines A (Figure 3a), B, 7, and 3S. This reflector can be traced intermittently from about 5 km south of the Gorda Escarpment to about 30 or 40 km south of the ridge and most likely represents the Moho [Henstock et al., 1997].

Lines A, 7, and B show a change in acoustic character of the top of acoustic basement about 13-16 km south of the Gorda Escarpment (point P, Figures 3 and 4). South of P on lines A, 7, and B, the top of acoustic basement is a rough, highly faulted surface (Figures 3 and 4). North of P, the interpreted top of acoustic basement is a strong north dipping reflector (Figures 3 and 4). The top-of-basement reflector can be traced on the MCS data to within 3-8 km of the Gorda Escarpment. This reflector is indistinct beneath the ridge, but models derived from gravity data along lines A, 7, and B suggest that the northern boundary of the Point Arena basin dips steeply south beneath the crest of the Gorda Escarpment (Figure 5). The top of basement in the gravity models is taken from the MCS data wherever the acoustic basement reflection is visible. Elsewhere, the basement is modeled to fit the short-wavelength free-air gravity anomaly. The combination of MCS and gravity data shows that the basement dips north to within about 13 km of the ridge (A, Figure 5b) before

Figure 5. Gravity data and density models (vertical exaggeration of 2) along multichannel seismic lines A, 7, and B. (a) Model gravity (solid line) plotted against observed gravity (dashed line) along line A. Gray line is model gravity for a model with a shallow basin edge. (b) Preferred density model geometry along line A. Segments A and B are referred to in the text. (c) Model gravity (solid line) plotted against observed gravity (dashed line) along line 7. (d) Preferred density model geometry along line 7. (e) Model gravity (solid line) plotted against observed gravity (dashed line) along line B. (f) Preferred density model geometry along line B. Tick marks above each gravity plot are for correlation with the map in Figure 1b. Numbers are density in g cm⁻³.
Figure 6. (a) True-scale seismic section of USGS line 32. Tick marks along the top of the section correspond to those on the map in Figure 1b. (b) Migrated, depth-converted section of line 32 with vertical exaggeration of 4. (c) Enlargement of Figure 6b showing the Gorda Escarpment region of line 32. (d) Line drawing of Figure 6c. Dips corrected for vertical exaggeration (Figures 6b-6d) are shown. (e) Migrated time section along MTJSE line 5. True scale at 4.8 km/s. Tick marks along the top of the section correspond to those on the map in Figure 1b. (f) Enlargement of Figure 6e showing the Gorda Escarpment region of line 5 (true scale at 4.8 km/s). (g) Line drawing of Figure 6f.

shallowing, first gently and then steeply, beneath the ridge (B, Figure 5b). On line B, the farthest of the three lines (A, 7, and B) from the triple junction, the northward dip of the basement reflector is about 5° (Figure 4b). On line A, the closest of the three lines to the triple junction, this dip has doubled to about 10° (Figures 3c and 3d).

The age of the sediments directly overlying basement in the northern Vizcaino block is unknown. We do, however, image the base of the upper Miocene section (horizon UM), the only dated horizon we have to work with, which is 1 km or less above the basement south of point P (Figures 3d and 3f). North of P, where the basement starts to dip northward, horizon UM rises, enclosing a wedge of sediments between it and basement that thickens toward the ridge (Figures 3d and 3f). The sediments within this wedge must be older than late Miocene (about 11 Ma) by some unknown amount. The sediments in this wedge onlap southward onto the strong, top-of-basement reflector and are truncated toward the ridge by horizon H (no age control), which is parallel to and about 0.4 km deeper than UM (Figure 3f). Sediments above horizon
4. Discussion

4.1. Evidence for Recent North-South Compression Across the Gorda Escarpment

The anomalously elevated Gorda Escarpment and tilted sediments eroded at the seafloor (e.g., lines 32, 5 and 7, Figures 4d and 6) indicate recent north-south compression across the Mendocino fracture zone. In the eastern part of the Vizcaino block (near line A where we have age control), this must have occurred since the late Miocene (about 11 Ma) as the tilted and eroded sediments lie above the base-of-upper-Miocene reflector (UM). This compression caused the ridge to "pop-up", tilting the northern edge of the Vizcaino block and exposing sediments at sea level, before subsiding to its current water depth. Gravity models (Figure 5 and Figure 7 of Leitner et al. [this issue]) show no crustal root beneath the ridge suggesting that present-day north-south compression is dynamically supporting the Mendocino Ridge [Leitner et al., this issue]. Strong north-south compression most likely began when the Blanco fracture zone initiated oblique to the east-west trending Mendocino transform at about 6 Ma [Wilson, 1986; Stoddard, 1987]. Prior to about 6 Ma, north-south compression across the Mendocino fracture zone was believed to be much less significant.

4.2. Origin of the Sedimentary Wedge Near the Triple Junction

We now discuss three possible ways in which the pre-upper Miocene sedimentary wedge may have formed: 1) north-south compression across the Mendocino fracture zone (Figures 8a-c), 2) structure preexisting on the Vizcaino block when the Vizcaino block was transferred from the North American to the Pacific plate (Figure 8e), and 3) east-west extension (Figures 8f-h).

4.2.1. North-south compression. The uplift of the Gorda Escarpment that caused the tilting and truncation of the youngest sediments (Figures 4 and 6) is evidence of north-south compression west of the triple junction since sometime after about 11 Ma (after the beginning of the late Miocene) in the vicinity of line 7 (Figure 1) where we have age control. It is therefore a separate, later north-south compressive event than that which may have formed the sedimentary wedge.

It is believed that there was no north-south compression across the Mendocino fracture zone between 19 and 10 Ma. Between 27 and 19 Ma, however, north-south compression across the fracture zone may have been possible (D. Wilson, personal communication, 1997) (Figures 8a-c).

If north-south compression across the Mendocino fracture zone was responsible for the formation of the sedimentary wedge, the onset of north-south compression at any point south of and close to the Mendocino fracture zone provides a time at which the triple junction was located east of that point (in a fixed Pacific plate reference frame) (Figures 8a-c). McCulloch [1987a, b] interpreted the southwest margin of the Vizcaino block as a late Oligocene/early Miocene paleosubduction-trench (Figure 8d) and implied (though did not explicitly state) that transform motion between the Pacific plate and the North American plate was taken up by oblique subduction at this paleotrench until about 16 Ma when the San Andreas initiated in its present-day position behind (east of) the trench (Figure 8a). A model calling on north-south compression, which is more likely before 19 Ma than between 19 and 10 Ma, requires the Vizcaino block being transferred to the Pacific plate before 19 Ma. Work on the Delgada fan, which overlies the Neogene Point Arena basin, suggests that the present geometry between the Mendocino triple junction, San Andreas fault, and Point Arena basin has existed at least since the Delgada fan started to form at 6-10 Ma [Drake et al., 1989]. Prior to 10 Ma, Drake et al. [1989] also suggest the plate boundary was at the subduction trench. If the triple junction, Mendocino fracture zone, and Point
The Arena basin have had their present geometry since the early Miocene or earlier, we should see evidence for compression throughout this time period (prior to about 16-0 Ma) in the north-east corner of the Vizcaino block (Figure 8a).

A model by Griscom and Jachens [1989, 1990] proposes that the triple junction jumped east over time (in one or more stages) such that it has been at its current position, with respect to the Pacific plate, only since about 5 Ma. This estimate was updated to 3 Ma by Parsons and Zoback [1997]. In the Griscom and Jachens [1989, 1990] model, the triple junction first intersected the Mendocino fracture zone farther west than its present position, at what is now the northwestern corner of the Vizcaino block (126°W in a present-day reference frame) [Griscom and Jachens, 1989, 1990] (Figure 8b). Over time, the triple junction jumped eastward, accompanied by eastward jumps of the San Andreas fault (or its past equivalents) and an eastward lengthening of the Mendocino transform fault [Griscom and Jachens, 1989, 1990]. Griscom and Jachens' [1989, 1990] model is based on the following: In the San Francisco Bay area, only about 22-23 km of a total of 300 km of strike-slip motion between the Pacific and North American plates has occurred on the San Andreas fault itself, the rest being presumably taken up on the San Gregorio fault and now extinct Pilarcitos fault that lie west of the San Andreas fault [Parsons and Zoback, 1997]. Farther north, Griscom and Jachens [1989, 1990] correlate magnetic and gravity highs in the Vizcaino block with rare magnetic and gravity highs to the south in the Franciscan complex east of the San Andreas fault. Realignment of these anomalies can be done by restoration along known faults only if there is also a fault west of the present San Andreas fault in the Vizcaino block. Griscom and Jachens [1989, 1990] extrapolate the Pilarcitos fault north through the Vizcaino block to the Mendocino fracture zone, arguing that it cannot rejoin the San Andreas fault south of the Mendocino fracture zone without cutting across the trend of the magnetic anomalies in the

Figure 8.
Zoback, 1997, a second jump east formed the present-day San block near the present-day position of the triple junction may expect to see evidence for one or more major strike-slip faults farther west prior to about 3 Ma (Figure 8b). We might also compression only from about 3 to 0 Ma in the northeast Vizcaino block along a continuation of the Pilarcitos fault (SAFI on Figure 8b), and finally, at about 3 Ma [Parsons and Zoback, 1997], a second jump east formed the present-day San Andreas fault just west of the present-day coastline (Figure 8c). If this model is correct, we should see evidence for compression only from about 3 to 0 Ma in the northeast corner of the Vizcaino block (Figure 8c) and compression farther west prior to about 3 Ma (Figure 8b). We might also expect to see evidence for one or more major strike-slip faults cutting through the Vizcaino block (Figures 8b and 8c).

North-south compression across the Mendocino transform fault concentrated in the northeast corner of the Vizcaino block near the present-day position of the triple junction may have resulted in downwarping of the top of basement, allowing the thick sedimentary wedge to be deposited against the transform fault. Line A (Figures 3e and 3f) shows sediments onlapping onto the basement, evidence for a deepening basement close to the escarpment. If so, compression was occurring sometime prior to about 11 Ma (base of upper Miocene), when the sediments beneath horizon UM (the upper surface of the sedimentary wedge) were deposited. The age of the oldest sediments in the northern part of the Point Arena basin is unknown, so timing of the onset of compression can be constrained only to a time before 11 Ma. It is thought that there was no compression between 19 Ma and 10 Ma but that compression prior to 19 Ma is possible [D. Wilson, personal communication, 1997]. If the sedimentary wedge formed as a result of north-south compression across the Mendocino transform fault sometime prior to 11 Ma, it must have occurred prior to 19 Ma. If north-south compression is also related to the presence of the triple junction, the Mendocino triple junction, Mendocino transform fault, and San Andreas fault must have had their present-day geometry from before 19 Ma to the present-day (Figure 8a). If this geometry has existed since before 19 Ma, it requires modification of the eastward jumping triple junction model of Griscom and Jachens [1989, 1990] (Figures 8d, 8b and 8c). The Mendocino triple junction and a proto-San Andreas fault could only have been located farther west along the Mendocino transform fault significantly before 19 Ma.

4.2.2 Preexisting structure. An alternative model is that the sedimentary wedge in the northeast corner of the Vizcaino block is a remnant of a forearc basin related to Farallon subduction (white region marked "e", Figure 8d). In this model, the forearc basin formed on the Vizcaino blocel, when it was part of the North American plate and was transferred with the Vizcaino block to the Pacific plate after the wedge was formed, i.e., after about 11 Ma, implying that the triple junction also arrived in its present-day position after 11 Ma. This model allows a "Griscom and Jachens" [1989, 1990]-like scenario, where the San Andreas fault jumps east over time.

Figure 8. (opposite) Tectonic models to explain the localized sedimentary wedge in the northeast corner of the Vizcaino block near the Mendocino triple junction. MFZ, Mendocino fracture zone; SAF, San Andreas fault; SAFI, proto-San Andreas fault; MTJ, Mendocino triple junction; PAC, Pacific plate; FAR, Farallon plate; NAM, North American plate; GOR, Gorda plate. Schematic cross section along line x-x is shown above each model. (a) Compressional model (this paper). Hachured area shows the region of the Vizcaino block predicted to be affected by compression across the Mendocino fracture zone. This region extends from the paleotrench (southwestern boundary of the Vizcaino block) to the present-day San Andreas fault, and no intermediate San Andreas transform is required. (b) and (c) Compressional model after Griscom and Jachens [1989, 1990]. This model assumes that the San Andreas fault initiated at the northwestern corner of the Vizcaino block west of its present-day position and jumped to its present position at the eastern boundary of the Vizcaino block accompanied by an eastward lengthening of the Mendocino transform fault at about 3 Ma. In Figure 8b, hachured area shows the region of the Vizcaino block west of the proto-San Andreas fault (SAFI) predicted to be affected by compression across the Mendocino fracture zone from 27 Ma to about 3 Ma. In Figure 8c, hachured area shows the region of the Vizcaino block west of the present-day triple junction predicted to be affected by compression across the Mendocino fracture zone from about 3 Ma to present-day. (d) Starting point for all models: Farallon-Pacific spreading prior to 27 Ma. The region that will become the Vizcaino block after the San Andreas initiates is currently part of the North American accretionary prism. White regions marked by letter e represent a preexisting forearc basin on the North American accretionary prism that will be required by the model shown in Figure 8e. (e) Model requiring a preexisting forearc basin on the North American plate accretionary prism (white regions in Figure 8d) which is transferred with the Vizcaino block to the Pacific plate when the San Andreas fault initiates in its present-day position (with respect to a fixed Pacific plate). (f) Extensional model based on a pull-apart basin formed at the northern end of the San Andreas fault due to the San Andreas fault and Cascadia subduction zone being non collinear. (g) and (h) Extensional model based on continued spreading at the subducted Farallon-Pacific ridge. In Figure 8g, sediments are deposited in a linear basin formed by east-west extension above the subducted spreading ridge. In Figure 8h, the San Andreas fault preferentially breaks through the crust at the location of the now extinct spreading ridge which lies beneath the wedge (this may also be true for all other models).
arriving in its present position (with respect to a fixed Pacific plate) relatively recently. The seismic data we have examined show no compelling evidence for a proto-San Andreas fault, a major plate boundary. The present-day San Andreas fault is a distinctive 2-4-km-wide shear zone [Ondrus, 1997], and we see nothing like it farther west in the Vizcaino block. McCulloch [1987a, b] cited evidence for a possible proto-San Andreas fault in the USGS data at the location of the Oconostota ridge. Recent migration of the USGS data set reveals the Oconostota ridge to consist of blind thrusts in the acoustic basement rather than a crustal-scale near-vertical strike-slip fault [Godfrey, 1997].

4.2.3. Extension. A third class of models explains the formation of the wedge by east-west extension during the "extensional phase" (25-15 Ma) of Leitner et al. [this issue]. Two mechanisms for extension in the northeast corner of the Vizcaino block are (1) extension due to transtension across the newly forming San Andreas fault, i.e., the sedimentary wedge is evidence of a pull-apart basin (Figure 8f) and (2) extension related to continued spreading of the Pacific-Farallon ridge after it was subducted [cf. Murdie et al., 1993] (Figures 8g and 8h).

4.2.3.1. Pull-apart basin formation. East-west extension may have occurred if the newly formed San Andreas transform fault was not collinear with the Cascadia subduction zone (Figure 8f). This geometry would result in east-west transtension between the northern end of the San Andreas fault and the southern end of the subduction zone, allowing a pull-apart basin to form in the northeast corner of the Vizcaino block [Ingersoll, 1982b] (Figure 8f). This model requires the triple junction to be east of the wedge (pull-apart basin) throughout the period the wedge formed and therefore constrains the triple junction to have been in its present location (with respect to the Mendocino transform fault and Point Arena basin) since before 11 Ma.

4.2.3.2. Extension over a subducted spreading ridge. If spreading continued for some time after the Farallon-Pacific spreading ridge was subducted beneath the North American margin, extension of the overlying crust may have occurred allowing a basin, now represented by the sedimentary wedge, to form [cf. Murdie et al., 1993] (Figure 8g). Depressional melting at the subducted ridge may also have underplated mafic material to the lower crust in the northeast corner of the Vizcaino block explaining the thick mafic lower crust beneath the triple junction region [Henstock et al., 1996; Leitner et al., this issue]. One drawback of this model is that we might expect an elongate basin overlying the subducted ridge rather than a wedge-shaped basin in the corner of the Vizcaino block (Figure 8g). The extinct ridge beneath the North American continent may have been a weak zone that allowed the San Andreas fault to preferentially break through the crust beneath the wedge (true for all models (Figures 8a, 8e, 8f and 8h)). If the wedge formed over the subducted spreading ridge and the San Andreas fault broke through the crust above the subducted ridge, the triple junction is constrained to have been at its present location since the wedge formed, i.e., since before 11 Ma, because the triple junction is always at the northern end of the San Andreas fault (Figure 8h).

4.3. Summary

Our data cannot conclusively prove which of these models for the formation of the sedimentary wedge is correct. Unless the wedge was a preexisting basin on the Vizcaino block when it was part of the North American plate that was transferred to the Pacific plate with the Vizcaino block, these models all suggest that the Mendocino triple junction was east of the sedimentary wedge during the time the wedge formed and therefore constrain the triple junction, San Andreas fault, and Point Arena basin to their present geometry since at least 11 Ma. Although we cannot yet choose between the models in Figures 8a, 8e, 8f and 8h, these hypotheses could be distinguished by drilling for age control in the northeastern corner of the Vizcaino block.

5. Conclusions

North-south compression sometime after about 11 Ma (more likely after about 6 Ma) across the plate boundary between the Pacific plate (which includes the Vizcaino block) and Gorda plate formed the Gorda Escarpment, an anomalously elevated region of the Mendocino fracture zone close to the Mendocino triple junction, east of 126°W.

Along the northern boundary of the Vizcaino block, except close to the triple junction, the Gorda Escarpment is overlain by a relatively thin sedimentary section that thins towards the crest of the escarpment. Close to the triple junction, there is a regionally-limited sedimentary wedge that formed prior to 11 Ma and that thickens towards the escarpment south of the Mendocino fracture zone. The strong spatial correlation between the sedimentary wedge in the northeast corner of the Vizcaino block and the Mendocino triple junction suggests the triple junction, San Andreas fault, and Point Arena basin have had their present geometry since before sediments were deposited to form the wedge (sometime before 11 Ma). Three possible models for the formation of the wedge are (1) formation as a pull-apart basin due to transtension at the northern end of the newly forming San Andreas fault, (2) formation due to east-west extension caused by continued spreading at the subducted Pacific-Farallon ridge, or (3) formation due to north-south compression across the Mendocino transform fault causing downwarping of the accretionary prism basement in the northeasternmost corner of the Vizcaino block toward the fracture zone, allowing a thick wedge of pre-11 Ma sediments to be deposited above it, against the Mendocino fault. Unless we explain the wedge as the remnant of a fortunately placed preexisting basin, all possible models suggest that the triple junction has been in its present position with respect to the Mendocino fracture zone and Point Arena basin since at least 11 Ma, and possibly since before 19 Ma.

Acknowledgments. We would like to thank Jon Childs and the National Geophysical Data Center for providing copies of the 1977 MCS data and Amoco Corporation and Sara Foland for providing copies of the industry data. We thank Craig Nicholson, Kate Miller, and Randy Keller for critical reviews that greatly improved this manuscript. Funding was provided by NSF Continental Dynamics grants EAR-9218209, EAR-9219598, and EAR-9526116.

References


Bachmann, S. B., M. B. Underwood, and J. S. Menack, Cenozoic evolution of coastal California, in Tectonics and Sedimentation Along