Active deformation of the Gorda plate: Constraining deformation models with new geophysical data

Jason D. Chaytor*
Chris Goldfinger — College of Oceanic and Atmospheric Sciences, Oregon State University, 104 Ocean Administration Building, Corvallis, Oregon 97331, USA
Robert P. Dziak — Cooperative Institute for Marine Resources Studies, Oregon State University/National Oceanic and Atmospheric Administration, Hatfield Marine Science Center, Newport, Oregon 97365, USA
Christopher G. Fox — National Oceanic and Atmospheric Administration, Pacific Marine Environmental Laboratory, Hatfield Marine Science Center, Newport, Oregon 97365, USA

ABSTRACT

The Gorda plate, the southernmost fragment of the larger Juan de Fuca plate system, is an example of a nonrigidly deforming tectonic accommodation zone or buffer plate, absorbing deformation and allowing the surrounding larger plates to act in a more rigid fashion. Here we present a new structural analysis of the plate based on full-plate bathymetric coverage, augmented by seismic reflection data and earthquake moment tensors and locations. We interpret internal deformation of the Gorda plate as an asymmetrical flexural-slip buckle with a vertical axis, utilizing reactivation of spreading-ridge fabric normal faults as strike-slip faults. Newly formed second-generation faults crosscutting the structural grain overprint the reactivated structures. The spreading fabric faults finally begin a second phase of extension as the plate approaches the subduction zone. This model, based on fault constraints, has allowed investigation of ridge-plate–subduction interactions, and suggests that spreading-rate variations along the Gorda Ridge may be controlled by internal deformation of the plate rather than the reverse, as previously hypothesized.

Keywords: marine geology, bathymetry, plate tectonics, faulting.

INTRODUCTION

Although plate tectonics was in its infancy, Raff and Mason (1961) recognized the Gorda plate region (Fig. 1) as unusual, noting the presence of strongly curved magnetic anomalies, which are significantly different from the ridge-parallel anomalies noted in other areas. This unusual deformation has inspired numerous attempts to explain it in a kinematic sense (e.g., Bolt et al., 1968; Silver, 1971; Riddihough, 1980; Knapp, 1982; Stoddard, 1987; Wilson, 1989). Each of these attempts was hindered by the limited resolution of available geophysical data as well as the inability to resolve a correlation between earthquake mechanisms and the causative faults.

We have been investigating the deformation of the Gorda plate by using new swath bathymetry covering the entire plate (Dziak et al., 2001). Analysis of these new data shows that internal nonrigid deformation is accomplished largely through reactivation of relict spreading-center faults by flexural slip; the plate also bears an overprint of newly formed second-generation faults and renewed extensional deformation as the plate approaches the subduction zone.

TECTONIC FRAMEWORK

The Gorda plate covers ~45,000 km^2 at the southern end of the Juan de Fuca plate, from which it is separated by the northwest-trending Blanco Fracture Zone (Fig. 1B). The Gorda plate is bordered on the west by the Gorda Ridge and on the south by the east-trending Mendocino Fracture Zone, both of which separate it from the Pacific plate. The eastern margin of the plate is being consumed in the Cascadia subduction zone at a rate of ~36–40 mm/yr (Riddihough, 1984). The Gorda plate is substantially more deformed and seismically active than the Juan de Fuca plate to the north and has had numerous large, intraplate, strike-slip earthquakes and a high level of intraplate microseismicity. This is the result of compression from the Pacific plate, nonparallelism of the bounding fracture zones, and the young age (0–7 Ma) of the unsubducted portion of the slab (Silver, 1971; Smith et al., 1993; Wilson, 1993).

At present, the half-spreading rates of the Gorda Ridge, based on magnetic anomaly patterns formed since 2 Ma (Wilson, 1989), are 27.5 mm/yr at the northern end of the ridge near the Blanco Fracture Zone and 14.0 mm/yr near the Mendocino Fracture Zone. Prior to 2 Ma, half-spreading rates were faster along both the northern (30–40 mm/yr) and southern (20–32.5 mm/yr) parts of the ridge, suggesting a major change in deformation style or mechanism at 2 Ma.

RESULTS

Morphostructural Mapping

The new bathymetric compilation covering the Gorda plate clearly shows the varied morphology and complex structural nature of the plate (Figs. 1A and 2). While deformation is occurring plate-wide, we broadly divide the plate into northern and southern segments, separated by a zone of more intense deformation.

The structural fabric within the northern zone (Fig. 2A) is characterized by north-northeast–trending (~020°) relict spreading-center ridges, paralleling the orientation of the northern Gorda Ridge. At their northernmost limit, where they meet the Blanco Fracture Zone, several of these ridges have been deformed into J structures (Sonder and Pockalny, 1999) reflecting the extensive shearing of the plate occurring at this seemingly inactive boundary (Fig. 2A). At the southern boundary of this zone, many of these faults are broken by left-lateral strike-slip faults, marking the transition to the plate's central deformation zone (Fig. 2A). Just west of the subduction-zone deformation front they show morphologies characteristic of renewed activity as dip-slip faults. Back-tilted and truncated near-surface sediments associated with these faults, as imaged by two-channel seismic reflection data (Line 170, EEZ-SCAN-84 Scientific Staff, 1986), suggest normal reactivation of these faults. A normal-fault interpretation would be most consistent with an extension mechanism at the initiation of plate bending (Chapple and Forsyth, 1979). Coincident with this zone of reactivation is the occurrence of both deformed and undeformed small seamounts of unknown age that may be the result of mid-plate volcanism related to local extension.

Within the central deformation zone (Fig. 2A), the morphology of the plate is dominated by a 130-km-long, 40-km-wide northwest-trending depression, which is on average 500 m deeper, but as much as 1000 m deeper, than the surrounding seafloor. This depression, the curved ridges flanking and cutting across it, and the proximity of the overlapping spread-

*E-mail: jchaytor@coas.oregonstate.edu.

ing center on the Gorda Ridge (OCS in Fig. 2A), suggest that this region may represent either a deformed overlapping spreading center–related propagation wake, or one of a series of parallel northwest-southeast–oriented folds within the Gorda lithosphere created by buckling induced by north-south compression (Dziak et al., 2001; Fig. 1A). Some of the most significant structural features related to the continuing deformation of the plate are found within this zone. The first of these is an ~100-km-long, left-lateral strike-slip fault trending between 030° and 055°, which begins near the spreading ridge and curves smoothly and continuously through the central depression, then merges with one of the reactivated normal faults within the northern part of the plate (Figs. 2A and 2C—marked in red). Evidence for variable amounts of displacement is present along the length of the fault (Fig. 2C), including left-lateral offsets of an as-yet-undated seamount (~1500 m) and a neighboring interridge channel (~1700 m). A minimum slip rate of between 0.75 and 0.85 mm/yr for this fault is given by the aforementioned offsets and the 2 Ma maximum age of the crust in this area given by the magnetic anomalies of Wilson (1993). This approximation may be only a fraction of the actual recent slip rate for this fault, if the ages of the seamount and interridge channel are significantly younger than the age of the crust on which they are found. Also prominent within this region is a northeast-trending (060°) lineation, clearly separating basement ridges of the northern segment from curved and rotated lineations of the central depression and southern plate segment (Figs. 2B and 2C—marked in orange). This lineation is the pseudofault of Wilson (1986), inferred from magnetic anomaly data. Seismic reflection data (Fig. DR1[1]) show surface and shallow-subsurface deformation at its northeast extension, consistent with reactivation as a left-oblique fault. This feature may continue northeastward in the subsurface, suggested by its alignment with a prominent indentation in the continental slope (Fig. 1A).

Analysis of the bathymetry of this central region has revealed the presence of numerous previously unknown northeast-trending (050°–055°) left-lateral strike-slip faults, which truncate and in places terminate into the north-northeast–trending basement ridges of the northern segment of the plate (Figs. 2A and 2C). The trend and slip direction of these active second-generation faults, however, provide a robust correlation with moment-tensor

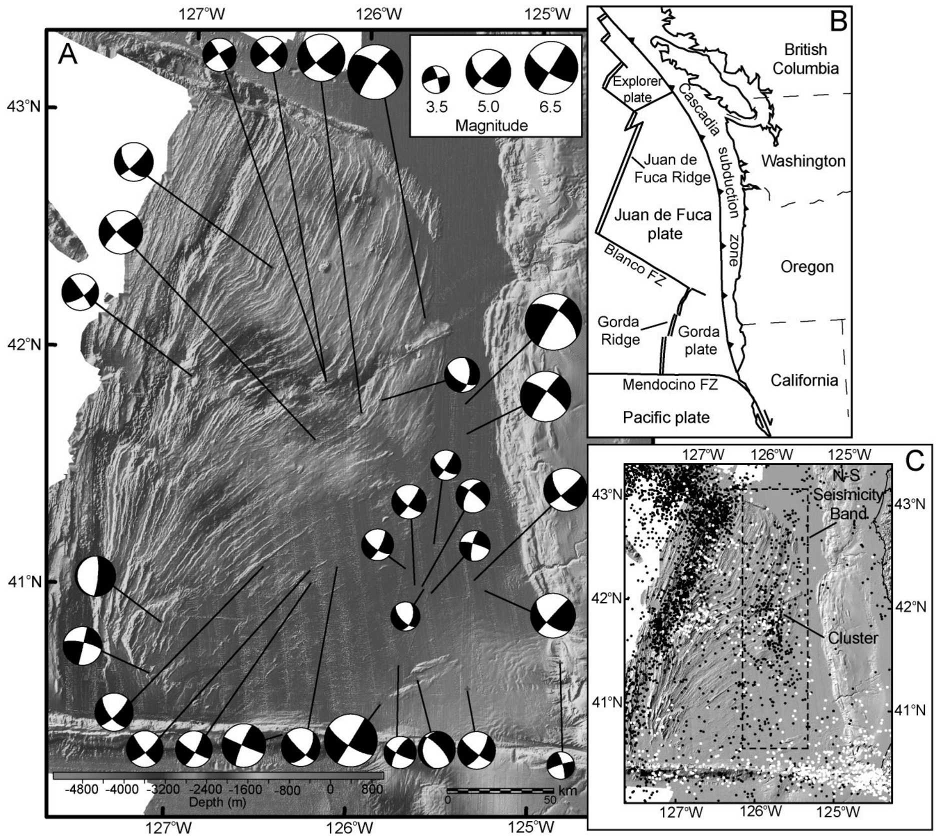

Figure 1. A: Shaded-bathymetric map of Gorda plate. Relict spreading-fabric basement ridges can be clearly seen; in places ridges are strongly deformed into smooth curves and kinks, whereas other ridges appear undeformed. Note northwest-trending deep depression in center of plate, small seamounts restricted to north half of plate, and strong northeast-trending lineation aligned with notch in margin. Moment-tensor solutions are from Oregon State University moment-tensor database (http://quakes.oce.orst.edu/moment-tensor/). B: Tectonic setting of Gorda plate (FZ = fracture zone). C: Seismicity of Gorda plate from 1974 to 2000. Note approximately north-south–oriented band of seismicity just west of Cascadia subduction zone deformation front and cluster of events in center of plate. White circles are from California Geological Survey database (1974–August 1991), and black circles are SOSUS events (August 1991–2000).

solutions for earthquakes occurring within this part of the plate (Fig. 1A). On the basis of the young morphology and strong correlation to moment tensor nodal planes, we infer that these faults are currently active and accommodating a significant proportion of the deformation occurring within the Gorda plate. The presence of a new generation of faults suggests either a reorientation of the principal stresses or that the first-generation faults have undergone enough internal rotation that new faults in a more favorable geometry have cut across the older structures.

Although they are partially covered by abyssal and channel sediments, the surface expressions of faults mapped in the southern segment correlate well with those mapped by Silver (1971) and Gulick et al. (2001) using seismic reflection data. As found to the north, bathymetric highs along these structures are offset left laterally, with slip occurring on relict spreading-center faults. The strong curvature and northeast strike of structures within this segment suggest progressive fanning of structures in a clockwise direction, with the southern end pinned against the Mendocino Fracture Zone and southern Gorda Ridge. This observation agrees with the interpretations of previous investigators, e.g., Riddihough (1980) and Gulick et al. (2001). The structural strikes remain consistent with the northeast-trending left-lateral fault planes of moment tensors, although offset features are more difficult to discern due to greater sedimentation (10 cm/1000 yr; Lyle et al., 1997), and conformity with existing faults.

Seismicity Correlations

By using hydroacoustic data from the U.S. Navy's Sound Surveillance System (SOSUS; Fox et al., 1994), the National Oceanic and Atmospheric Administration (NOAA) has been recording earthquake locations in the northeast Pacific since August 1991 without the 30–40 km eastward shift present in land-station–derived locations (Stoddard and

[1]GSA Data Repository item 2004057, subbottom profile, is available online at www.geosociety.org/pubs/ft2004.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

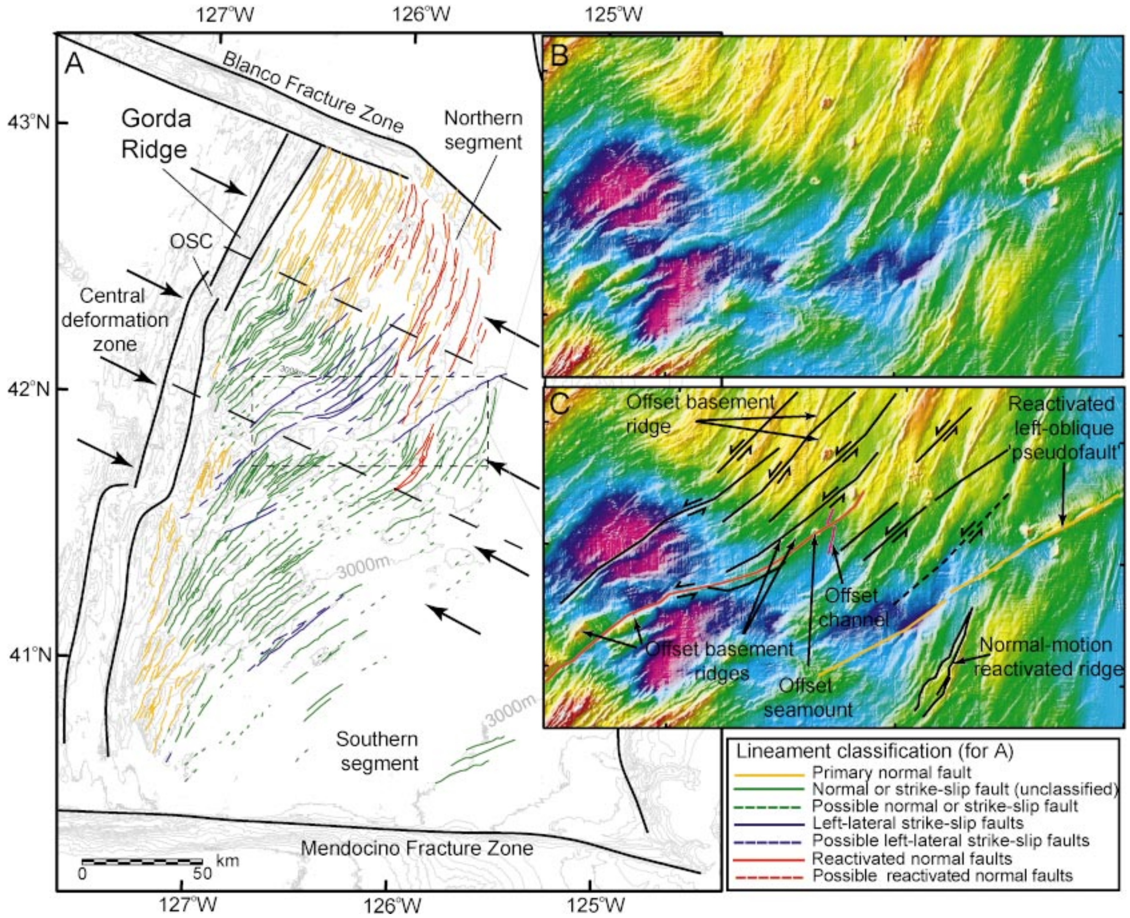

Figure 2. A: Mapped faults and fault-related ridges within Gorda plate based on basement structure and surface morphology, overlain on bathymetric contours (gray lines—250 m interval). Approximate boundaries of three structural segments are also shown. Black arrows indicated approximate location of possible northwest-trending large-scale folds. B, C: Uninterpreted and interpreted enlargements of center of plate showing location of interpreted second-generation strike-slip faults and features that they appear to offset. OSC—overlapping spreading center.

Woods, 1990). These data show an approximately north-south–oriented band of seismicity just west of the deformation front of the Cascadia subduction zone, and a cluster of seismicity in the central region of the plate probably related to the second-generation faults (Fig. 1C). This band of seismicity is well correlated with the location of faults that we have interpreted to be undergoing normal reactivation. This correlation suggests that these faults (1) reflect the presence of outer rise slab-bending extension (Fox and Dziak, 1999), (2) reflect east-west extension due to the north-south compression that is driving the flexural slip buckle, or, most likely, (3) reflect a combination of both.

To further test fault-slip directions and structural correlations, we compared the locations and moment-tensor solutions of Nabelek and Xia (1995; Pacific Northwest broadband stations, 1990–1998) to our morphostructural interpretation. Significant correlation is found between earthquake locations and the position and inferred slip direction of the reactivated basement ridges and the newly identified second-generation strike-slip faults. In a number of cases, within the error of the locations, the nodal planes of moment-tensor solutions associated with these events show a direct correlation to the strike of the faults on which they occur, with ~90% of these planes found to be within 5° of the mapped fault strikes. This result can be seen in Figure 1A.

DISCUSSION AND CONCLUSIONS

The analysis of the new bathymetric data set, coupled with the correlation of moment tensors and earthquakes locations with mapped features, provides an opportunity to evaluate previously proposed models of Gorda deformation. Several of these models (Riddihough, 1980; Knapp, 1982; Bolt et al., 1968; Figs. 3A–3C) relied on the development of large-scale northwest-trending right-lateral strike-slip faults and rigid block movement in order to account for the more eastward location of the pre–2 Ma magnetic anomalies and variability of observed basement-ridge orientations. On the basis of the bathymetry and available seismic reflection data, there appears to be no fault or lineation that would correspond to such large-scale features. Similarly, no evidence was found to support the near-ridge northwest-trending right-lateral shear zone component of the model proposed by Wilson (1989; Fig. 3D). By using both the magnetic anomaly data and regional GLORIA side-scan data, Masson et al. (1988; Fig. 3E) suggested a deformation model driven solely by clockwise rigid-block rotation of the entire plate. Continuous curvature (though kink bands like those of Masson et al. [1988] are present) of the basement ridges, however, can be clearly seen in the bathymetry, requiring a nonrigid-block deformation mechanism. Figure 3F shows a flexural-slip buckling model first proposed by Silver (1971) and later investigated and modified by Stoddard (1987, 1991). In this model the Gorda plate is actively deforming in a flexural-slip faulting style (Yeats, 1986), but in the horizontal plane. Our data support this type of model, with several stages of deformation (Fig. 3G). The first stage involved reactivation of relict, spreading-center–normal faults inherited from the Gorda Ridge. As crust moved eastward away from the ridge, left-lateral slip occurred along the faults, the ends of which move closer together owing to the nonparallel arrangement of the bounding fracture zones. This squeezing of the Gorda plate under north-south compression between the older Pacific and Juan de Fuca plates accommodated flexure of the plate into an asymmetrical syncline with a vertical axis, allowing for the observed curvature and kinking of the lineations near the ridge. As deformation continued, the second-generation faults broke across the previously reactivated fabric. Just to the west of the subduction front, where the microseismic-

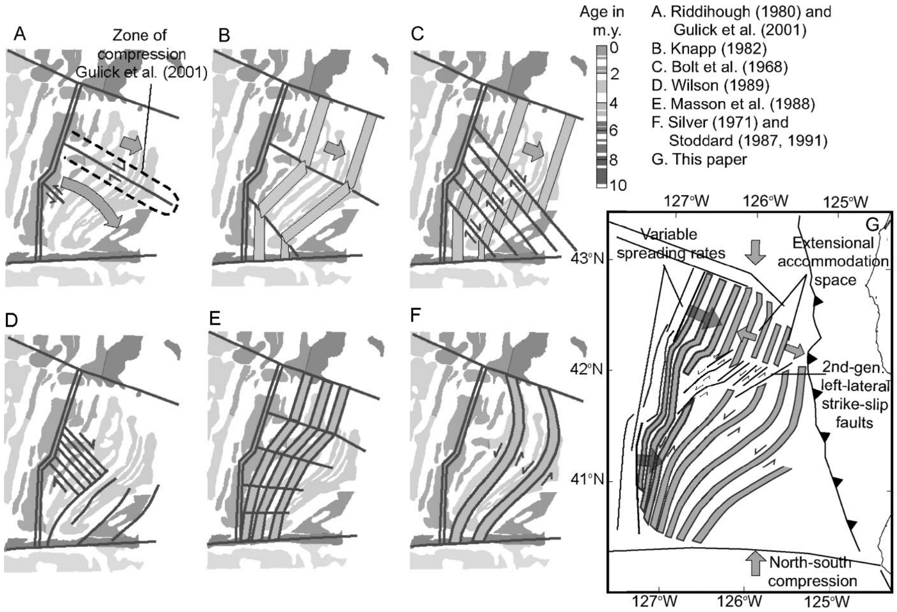

Figure 3. Models of brittle deformation for Gorda plate overlain on magnetic anomalies modified from Raff and Mason (1961). Models A–F were proposed prior to collection and analysis of full-plate multibeam data. Deformation model of Gulick et al. (2001) is included in model A. Model G represents modification of Stoddard's (1987) flexural-slip model proposed in this paper.

ity is at its highest level, outer-rise east-west–bending extension is superimposed on the syncline, and further extension may occur as the flexural slip buckle continues to grow. The reactivated pseudofault accommodates further north-south shortening.

Although many aspects of the deformation still remain unclear, narrowing the field of kinematic models provides an opportunity to gain a better understanding of the relative importance of each of the principal plate-driving mechanisms in creating the observed deformation patterns. Whereas in the past the case has been made for spreading-rate–induced changes in deformation, the preliminary deformation model described here may provide a mechanism for changes in spreading rate driven by the deformation. In other words, the deformation may not have to be driven by spreading-rate changes; rather, the deformation may open accommodation space along the northern Gorda Ridge as a consequence of the internal deformation, allowing a higher spreading rate. The active extensional processes and abundant and seemingly anomalous off-axis volcanism localized in the northern half of the plate suggest that accommodation space is opening at rates that exceed the spreading rate. This conclusion implies (1) that spreading rates along ridge segments associated with deforming microplates are controlled largely by internal deformation rates within the plate, which in essence makes the ridges passive features that respond to the deformation, or (2) that spreading rates reflect an interplay between ridge spreading and the deforming plate.

ACKNOWLEDGMENTS

This research was funded by National Science Foundation grant OCE-9912292 (Goldfinger). Collection of SeaBeam bathymetric data was supported by the National Oceanic and Atmospheric Administration Vents Program. We thank Sean Gulick and Greg Moore for helpful reviews.

REFERENCES CITED

Bolt, B.A., Lomnitz, C., and McEvilly, T.V., 1968, Seismological evidence of the tectonics of central northern California and the Mendocino escarpment: Seismological Society of America Bulletin, v. 58, p. 1725–1767.

Chapple, W.M., and Forsyth, D.W., 1979, Earthquakes and bending of plates at trenches: Journal of Geophysical Research, v. 84, p. 6729–6749.

Dziak, R.P., Fox, C.G., Bobbitt, A., and Goldfinger, C., 2001, Bathymetric map of the Gorda plate: Structural and geomorphological processes inferred from multibeam surveys: Marine Geophysical Researches, v. 22, p. 235–250.

EEZ-SCAN-84 Scientific Staff, 1986, Atlas of the Exclusive Economic Zone, western conterminous United States: U.S. Geological Survey, 152 p.

Fox, C.G., and Dziak, R.P., 1999, Internal deformation of the Gorda plate observed by hydroacoustic monitoring: Journal of Geophysical Research, v. 104, p. 17,603–17,615.

Fox, C.G., Dziak, R.P., Matsumoto, H., and Schreiner, A.E., 1994, Potential for monitoring low-level seismicity on the Juan de Fuca Ridge using fixed hydrophone arrays: Marine Technology Society Journal, v. 27, p. 22–30.

Gulick, S.P.S., Meltzer, A.S., Henstock, T.J., and Levander, A., 2001, Internal deformation of the southern Gorda plate: Fragmentation of a weak plate near the Mendocino triple junction: Geology, v. 29, p. 691–694.

Knapp, J.S., 1982, Seismicity, crustal structure, and tectonics near the northern termination of the San Andreas fault [Ph.D.thesis]: Seattle, University of Washington, 316 p.

Lyle, M., Koizumi, I., Richter, C., and Ship Scientific Party, 1997, Site 1020, California margin Leg 167, *in* Lyle, M., Koizumi, I., et al., Proceedings of the Ocean Drilling Program: Initial reports, Volume 167: College Station, Texas, Ocean Drilling Program, p. 389–429.

Masson, D.G., Cacchione, D.A., and Drake, D.E., 1988, Tectonic evolution of Gorda Ridge inferred from sidescan sonar images: Marine Geophysical Researches, v. 10, p. 191–204.

Nabelek, J., and Xia, G., 1995, Moment-tensor analysis using regional data: Application to the March 25, 1993, Scotts Mills, Oregon, earthquake: Geophysical Research Letters, v. 22, p. 13–16.

Raff, A.D., and Mason, R.G., 1961, Magnetic survey off the west coast of North America, 40°N. latitude to 52°N. latitude: Geological Society of America Bulletin, v. 72, p. 1267–1270.

Riddihough, R.P., 1980, Gorda plate motions from magnetic anomaly analysis: Earth and Planetary Science Letters, v. 51, p. 163–170.

Riddihough, R.P., 1984, Recent movements of the Juan de Fuca plate system: Journal of Geophysical Research, v. 89, p. 6980–6994.

Silver, E.A., 1971, Tectonics of the Mendocino triple junction: Geological Society of America Bulletin, v. 82, p. 2965–2978.

Smith, S.W., Knapp, J.S., and McPherson, R.C., 1993, Seismicity of the Gorda plate, structure of the continental margin, and an eastward jump of the Mendocino triple junction: Journal of Geophysical Research, v. 98, p. 8153–8171.

Sonder, L.J., and Pockalny, R.A., 1999, Anomalously rotated abyssal hills along active transforms: Distributed deformation of oceanic lithosphere: Geology, v. 27, p. 1003–1006.

Stoddard, P.R., 1987, A kinematic model for the evolution of the Gorda plate: Journal of Geophysical Research, v. 92, p. 11,524–11,532.

Stoddard, P.R., 1991, A comparison of brittle deformation models for the Gorda plate: Tectonophysics, v. 187, p. 205–214.

Stoddard, P.R., and Woods, M.T., 1990, Master event relocation of Gorda block earthquakes: Implications for deformation: Geophysical Research Letters, v. 17, p. 961–964.

Wilson, D.S., 1986, A kinematic model for the Gorda deformation zone as a diffuse southern boundary of the Juan de Fuca plate: Journal of Geophysical Research, v. 91, p. 10,259–10,269.

Wilson, D.S., 1989, Deformation of the so-called Gorda plate: Journal of Geophysical Research, v. 94, p. 3065–3075.

Wilson, D.S., 1993, Confidence intervals for motion and deformation of the Juan de Fuca plate: Journal of Geophysical Research, v. 98, p. 16,053–16,071.

Yeats, R.S., 1986, Active faults related to folding, *in* Wallace, R.E., ed., Active tectonics: Studies in geophysics: Washington, D.C., National Academy of Sciences Press, p. 63–79.

Manuscript received 16 September 2003
Revised manuscript received 5 December 2003
Manuscript accepted 8 December 2003

Printed in USA