

# Internal deformation of the southern Gorda plate: Fragmentation of a weak plate near the Mendocino triple junction

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## ABSTRACT

North-south compression across the Gorda-Pacific plate boundary caused by the northward-migrating Mendocino triple junction appears to reactivate Gorda plate normal faults, originally formed at the spreading ridge, as left-lateral strike-slip faults. Both seismically imaged faults and magnetic anomalies fan eastward from  $\sim N20^{\circ}E$  near the Gorda ridge to  $\sim N75^{\circ}E$  near the triple junction. Near the triple junction, the Gorda plate is faulted pervasively and appears to be extending east-southeast as it subducts beneath North America. Continuation of northeast-southwest-oriented deformation in the southern Gorda plate beneath the continental margin contrasts with the northwest-southeast-trending structures in the overlying accretionary prism, suggesting partial Gorda-North American plate decoupling. Southeast of the triple junction, a slabless window is generated by removal of the subducting Gorda plate. Southwest of the triple junction, the Pacific plate acts as a rigid barrier forcing southern Gorda crust to rotate clockwise, fragment, and flow into the slabless window. Net clockwise rotation of the southern Gorda crust forms a boundary with the nonrotating northern Gorda plate, which is observed as a bend in the magnetic anomalies. This boundary, which is compressional on the western end and extensional to the east, may separate the stress regime of the southern Gorda plate from the remainder of the Cascadia subduction zone.

**Keywords:** Mendocino triple junction, Gorda plate, plate boundary, deformation, fragmentation.

## INTRODUCTION

The Gorda microplate subducts northwest of the Mendocino triple junction (Atwater, 1970); evidence of deformation within the microplate led Wilson (1986) to term its southern part the Gorda deformation zone (Fig. 1). West of the triple junction, the Mendocino fracture zone separates the 25–27 Ma Pacific plate from the 0–7 Ma Gorda plate. Southeast of the triple junction is a slabless window where removal of the subducting Gorda lithosphere from beneath North America causes asthenospheric upwelling (Dickinson and Snyder, 1979).

Gorda plate magnetic anomalies 2, 2A, and 3 are kinked between the northern and southern Gorda plate (Fig. 1) (Raff and Mason, 1961; Silver, 1971). North of this kink, the anomalies parallel the Gorda ridge. South of the bend, the anomalies trend obliquely to the ridge, progressively changing from  $N35^{\circ}E$  (anomaly 2) near the spreading ridge to  $N65^{\circ}E$  (anomaly 4) near the triple junction. Silver (1971) noted that the Gorda plate magnetic anomalies are tens of kilometers shorter than the corresponding Pacific plate anomalies.

Seismicity is concentrated in the southern

Gorda plate near the triple junction and diminishes rapidly south of the Mendocino fracture zone (Fig. 2A). Focal mechanism and moment tensor solutions define stress orientations, which suggest that the Gorda plate is being deformed within the plate interior by northeast-southwest-trending, left-lateral strike-slip faults (Wilson, 1986).

Direct evidence for a northeast-southwest orientation of the faults (Fig. 2A) in the northwestern Gorda plate comes from single-channel seismic data (Silver, 1971) and surface expressions of fault-related basement ridges imaged on GLORIA sidescan sonar data (EEZ-SCAN 84 Scientific Staff, 1986; Wilson, 1986). This orientation is also suggested in the aftershock sequence of the magnitude 7.2 Eureka, California, seismic event on November 8, 1980 (Wilson, 1989).

We present multichannel seismic reflection data from the Mendocino triple junction seismic experiment (Tréhu et al., 1995) that image the southeastern Gorda plate in advance of the migrating Mendocino triple junction (Fig. 1A). When integrated with single-channel seismic, GLORIA, seismicity, and magnetic anomaly data, these profiles provide an improved understanding of kinematics of the Gorda plate. Specifically, the internally deforming southern Gorda plate is rotating clockwise toward the triple junction. This rotation creates a boundary with the northern

Gorda plate that may serve as the northern limit of influence of the triple junction on the Juan de Fuca–Gorda plate system. Near the triple junction, the plate shows evidence of fragmenting (Fig. 1B).

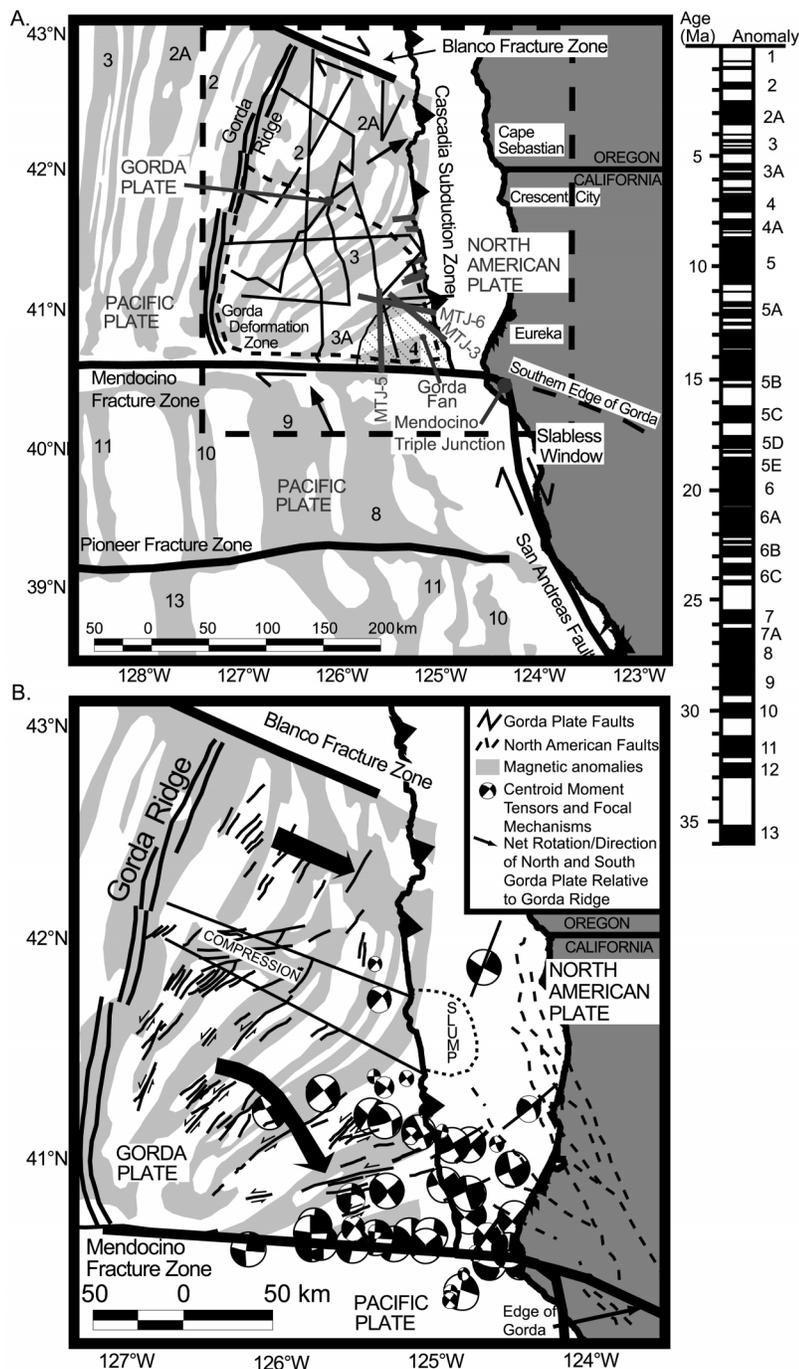
## GORDA PLATE DEFORMATION

Oceanic crust imaged on seismic lines MTJ-3, MTJ-5, and MTJ-6 is rough and pervasively faulted (Fig. 3). The crust appears in places to be broken into crustal blocks bounded by major faults and deformed by minor faults (Fig. 3, A and B; Gulick et al., 1998). High-angle faults, imaged in the southeastern Gorda plate, have on average eastward dips of up to  $80^{\circ}$  and lack evidence of shortening within the sediments they cut (Fig. 3). Southeast-side-down basement offsets overlain by southeast-downthrown or seaward-tilted sediments (Fig. 3, B and C) suggest a component of extension. We interpret these faults as primarily strike-slip, consistent with earthquake data (Fig. 2A), with a secondary component of east-southeast extension not reflected in the modern earthquake record. Pervasive faulting suggests crustal-scale fragmentation of the brittle part of the Gorda plate near the triple junction.

Paralleling the Gorda ridge in the northern Gorda plate, faults with an orientation of  $N20^{\circ}$ – $30^{\circ}E$  (Silver, 1971) are truncated at their southern end by a series of faults trending  $N80^{\circ}E$  (Fig. 2A). In the southern Gorda plate, faults trend  $N20^{\circ}$ – $N45^{\circ}E$  near the Gorda ridge, but they rotate clockwise along the Mendocino fracture zone to an orientation of  $N75^{\circ}E$  in the southeast, subparallel to the anomalies. In the southeast Gorda plate, a region of seafloor scarps observed on the GLORIA data (Fig. 2A) is coincident with the region of shallow crust and fault scarps imaged on MTJ-5 (Fig. 3A). This map view indicates constraints for some of the faults on MTJ-5 to  $\sim N70^{\circ}E$ . Where MTJ-5, MTJ-6, and MTJ-3 are in proximity, prominent mappable faults have general east-northeast orientations (Fig. 2B), consistent with the progressively more eastward-oriented pattern of basement ridges and faults. This apparent relationship suggests that these faults may have formed at the spreading ridge but were later reactivated as strike-slip faults (Wilson, 1989).

Depth-to-basement structure contours (Fig.

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**Figure 1. A:** Gorda plate study area showing plate boundaries with Pacific and North American plates. Gray areas are magnetic anomalies (Atwater and Severinghaus, 1988); dashed line indicates Gorda deformation zone (Wilson, 1986); area with dotted lines is Gorda fan. Anomaly ages (Ma) are shown to right. Dark gray lines are parts of industry and academic multi-channel data; black lines are single channel seismic data of Silver (1971). Bold arrows show Gorda and Pacific plate motions relative to stable North America. Heavy-dash box indicates area of B. **B:** Tectonic model for Gorda plate, where boundary between rotating southern Gorda crust and more stable northern Gorda crust is shown along bend in anomalies. Dashed-line circular area east of Cascadia deformation front is collapsed part of prism (Gulick, 1999). Dashed lines are upper plate structures that contrast with Gorda plate fault orientations.

2A) show an arcuate break in basement slope. Basement contours parallel the Cascadia deformation front in the northern Gorda plate, but trend northeast-southwest in the southern

Gorda plate, dipping east-southeast down to >4750 m (Fig. 2). Gorda basin sediment thickness increases dramatically from ~500 m at the break in basement slope to >2500 m at

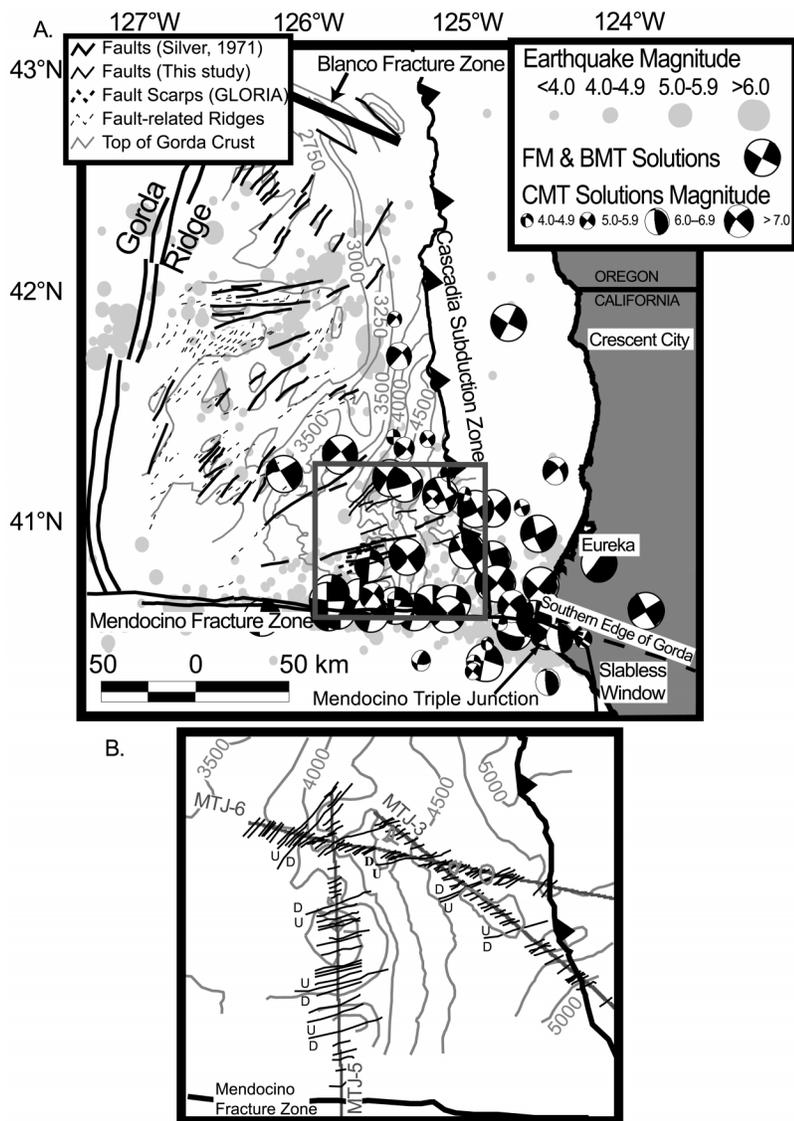
the deformation front. Uplift and erosion of the continental margin in proximity to the triple junction (Gulick, 1999) provide a sediment source with transport down the Eel Canyon and deposition of the Gorda fan (Fig. 1A), which is coincident with the deepest oceanic basement.

## DISCUSSION

Eastward-fanning geometry of southern Gorda plate faults and magnetic anomalies suggests clockwise rotation of the southern part of the Gorda plate (Riddiough, 1980), resulting in a boundary with the nonrotating northern Gorda plate (Fig. 1B). Clockwise rotation of the southern plate is consistent with compression along the western end of the bend of the magnetic anomalies (Fig. 1B), where we observe faults oriented N80°E and a shallow basement ridge (Fig. 2A) (Silver, 1971). Clockwise rotation also predicts extension along this boundary somewhere to the east. Seismic stratigraphic analysis (Gulick, 1999) concluded that part of the forearc overlying the subducting eastern end of the bend in the anomalies collapsed within the past 500 k.y., consistent with the subduction of either topography or a crustal-scale graben related to this boundary (Fig. 1B). The boundary between the rotating and nonrotating parts of the Gorda plate may be the northern limit of the influence of the triple junction on the Juan de Fuca–Gorda plate system.

Fox and Dziak (1999) reported a band of microseismicity that trends north-northeast across the bend in the magnetic anomalies and oblique to the trends of the southern Gorda plate faults. Given the discrepancy with mapped faults and basement ridges, we interpret these events to represent stress relief from plate bending forces generated by the plate subduction.

Seismic transects MTJ-5 and MTJ-3 (Fig. 3) and available seismicity data (Fig. 2) show no evidence for underthrusting of the Gorda plate beneath the Pacific plate or obduction of the Gorda plate onto the Pacific plate; these suggestions were made by Silver (1971) and Stoddard (1987), respectively, to explain the shortened Gorda plate magnetic anomalies. We suggest an alternative: a combination of shearing of the anomalies along the fracture zone suggested by changes in anomaly shape, shortening of the crust near the spreading ridge due to convergence between the northern and southern parts of the Gorda plate, and a component of nonparallel strike-slip deformation observed in the structural mapping (Fig. 1B). A small zone of northwest-southeast-oriented deformation near the spreading ridge proposed by Wilson (1989) is also possible. The seismic transects, lithospheric strength calculations (Henstock et al., 1999), gravity modeling (Leitner et al., 1998), and cessation of seismicity



**Figure 2. A:** Mapped faults and fault-related basement ridges within Gorda plate overlain on global seismic network events. Gray lines are structure contours for top of Gorda crust labeled in meters below sea level. Depth to basement data are from Mendocino experiment multichannel, industry multichannel, and Silver (1971) single-channel seismic lines. Note break in basement slope at ~3500 m and general east-southeast dip of basement in southeastern Gorda plate. Focal mechanism (FM) solutions are from McPherson (1992) and Bolt et al. (1968); Berkeley moment tensor (BMT) solutions are northern California seismic network events (Pasyanos et al., 1996); centroid moment tensor (CMT) solutions are Harvard global events (Dziewonski et al., 1981). Focal mechanisms east of deformation front are >15 km deep and within subducting plate. Gray box indicates area of B. **B:** Southeastern Gorda plate with all interpreted faults from MTJ-5, MTJ-6, and MTJ-3 and contours of top of subducting crust. Major faults are thicker and labeled with relative basement offset.

(Wilson, 1986) suggest that Pacific lithosphere is acting as a rigid barrier.

Similarity of the focal mechanism solutions from within the Gorda plate west and east of the deformation front (Fig. 1B), analysis of the Humboldt Bay seismic network events by McPherson (1992), and the mapping of the left-lateral faults up to the deformation front suggest that the faults imaged in the Gorda plate continue beneath the margin. Although we were unable to trace individual faults beneath the margin, seismic images from the de-

formation front show highly deformed crust beneath the décollement (Gulick et al., 1998). Northwest-southeast-oriented structures within the overlying forearc (Gulick, 1999) contrast with subducted, seismically active (Fig. 2A), northeast-southwest-oriented Gorda plate structures and imply partial frictional decoupling between the Gorda and North American plates. Critical wedge mechanics arguments (Gulick et al., 1998), and a north-south  $\sigma^1$  determined by the inversion of 70 focal mechanism solutions (Schwartz and Hubert,

1997), which is oblique to east-northeast subduction, also require a weak décollement.

Increase in seismicity and pervasive faulting of Gorda crust in the southeast suggest that the plate is breaking up near the triple junction (Figs. 2 and 3). Reflections from the top of subducting Gorda crust on seismic transects in this region are discontinuous beneath the accretionary prism (Gulick, 1999), consistent with fragmentation of the crust. In contrast, a seismic transect from north of the bend in the magnetic anomalies clearly images the subducting plate for 60 km east of the deformation front (Gulick, 1999).

In a fixed Pacific plate reference frame, the Gorda plate is moving 65 mm/yr at  $112^\circ$ , which results in net Pacific-Gorda convergence. Seismic images of a pervasively faulted, extending, and fragmented Gorda crust near the triple junction support a recent revision of the slabless window model by Henstock et al. (1999), who postulated flow of Gorda fragments into the slabless window east of the northern San Andreas fault, past the edge of the rigid Pacific plate.

## CONCLUSIONS

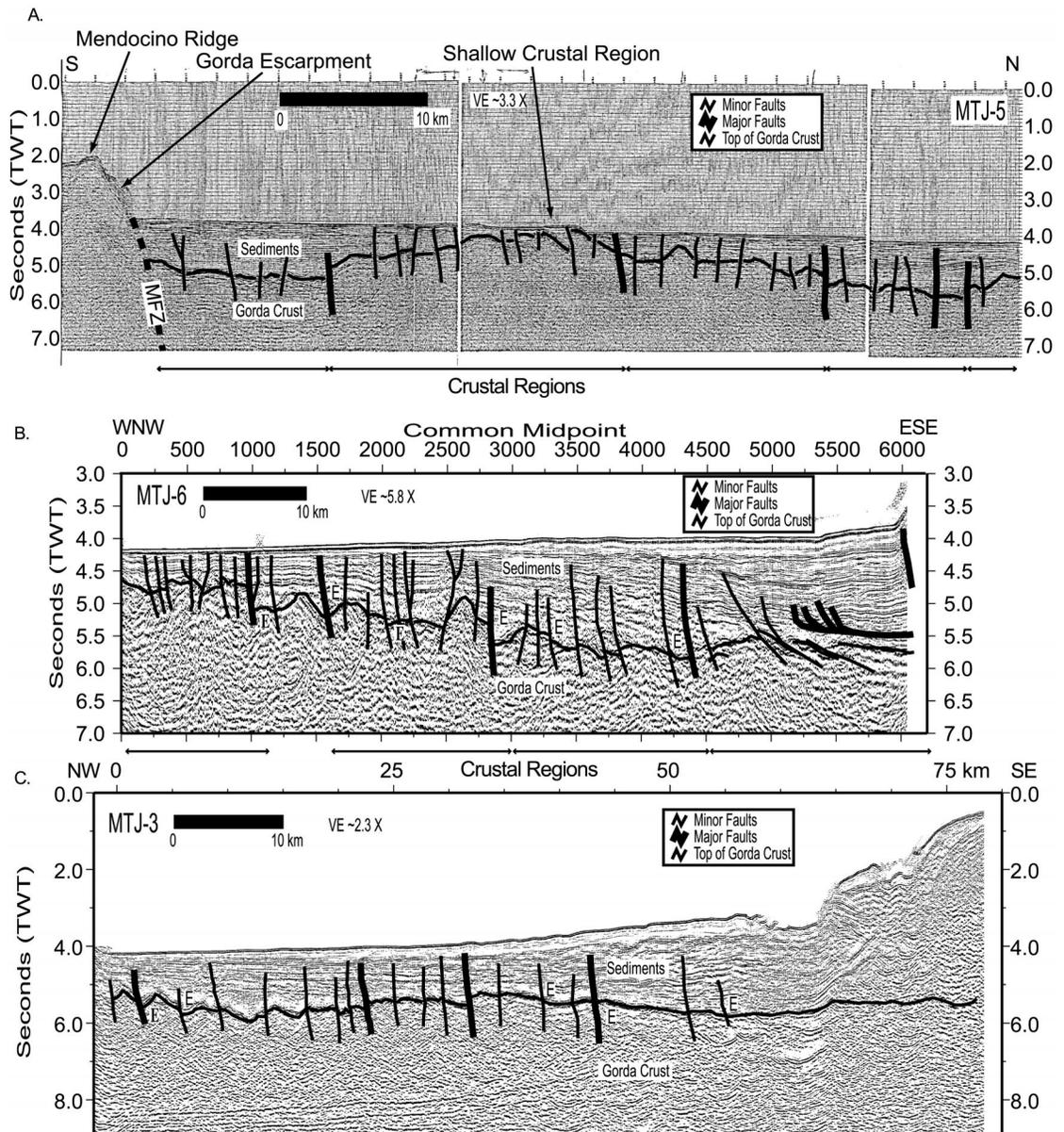
North-south compression caused by net convergence across the Gorda-Pacific plate boundary causes the Gorda plate to rotate clockwise and deform along northeast-southwest left-lateral strike-slip faults. Continuation of these northeast-southwest-oriented faults beneath the accretionary prism contrasts with northwest-southeast-oriented structures observed in the overlying forearc basin, suggesting decoupling between the Gorda and North American plates. At the Mendocino triple junction, the Gorda plate is fragmenting, as the crust appears to rotate into the region east of the San Andreas and the edge of the Pacific plate. The clockwise-rotating southern Gorda plate is truncated by a tectonic boundary with the nonrotating northern Gorda plate, a boundary observed as a bend in the magnetic anomalies. This boundary may represent the northern limit of the influence of the Mendocino triple junction on the Juan de Fuca-Gorda plate system.

## ACKNOWLEDGMENTS

We thank the crew of the R/V *Maurice Ewing* for aid in data collection. D. Merritts and two anonymous readers provided excellent reviews. Supported by National Science Foundation grants EAR-9219598 and EAR-9526116 to Lehigh University.

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**Figure 3.** Mendocino seismic lines with numerous high-angle faults where larger offset faults appear to divide crust into blocky crustal regions. **A:** Line MTJ-5 trending north-south shows Pacific-Gorda plate boundary. Mendocino fracture zone (MFZ) separates acoustically transparent Pacific crust and metasediments beneath escarpment from >1 km of Gorda basin sediments. **B:** Profile MTJ-6 showing 75 km of Gorda plate west of Cascadia subduction zone. Note contrast in basement versus sediment offset on some faults. **C:** MTJ-3 transect trending 75 km N56°W from near triple junction to the Gorda basin. E = extension.

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Manuscript received October 26, 2000  
 Revised manuscript received March 27, 2001  
 Manuscript accepted April 10, 2001

Printed in USA