Utilizing Compressive Growth Structure for Calculating Slip Rates on Buried Thrust Faults
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G.P.S., Seismicity, and Structural Analysis

During this past year we integrated G.P.S. measurements and regional seismicity with our structural analyses of blind thrust fault systems in the Santa Barbara Channel and Los Angeles Basin, CA. G.P.S. shortening rates and directions are compared with fault slip rates to estimate the percentage of crustal shortening accommodated on recognized faults. Also, recent swarms of seismicity along the Offshore Oak Ridge trend may be associated with folding of rock through an active axial surface by bedding parallel slip. These folding earthquakes help locate major blind thrust faults and may locate segment boundaries for damaging earthquakes on the underlying causative fault systems.

G.P.S. Measurements and Slip on
Active Thrust Faults in the Santa Barbara Channel

Analysis of compressive growth structures in the eastern Santa Barbara Channel indicates Recent NE-SW shortening caused by slip on subsurface blind thrust faults. Analysis of syntectonic (growth) sediments (Suppe et al., 1992) along the Offshore Oak Ridge trend (Fig. 1) yields a 1.3 mm/year slip rate on the underlying Deep Channel thrust (Fig. 2). In addition, compressive growth structure along the Blue Bottle trend yields a combined 1.1 mm/year slip rate on shallower 2 - 5 km deep thrusts (Shaw and Suppe, 1991; Shaw et al., 1992). The NE-SW slip direction is consistent with the direction of the horizontal component of the maximum compressive stress (Mount, 1989), recent earthquake P-axes, and the 029°±10° shortening direction measured by geodesy (Larson, 1990) (Fig. 1). This slip direction is also compatible with the relative North American-Pacific Plate motions (Demets et al. 1987) and the length and width of Santa Cruz Island that is uplifted by movement on the Deep Channel thrust (Fig. 2).

The combined Plio-Quaternary fault slip rates calculated for the channel faults (2.4 mm/year) may account only for a fraction of the 7±5 mm/year NE - SW shortening across the channel measured by geodesy (Larson, 1990). This combined slip may also accommodate only about one quarter of the regional shortening directed normal to the San Andreas Fault (Demets et al. 1987). This shortening resolves the normal component of the vector that describes the discrepancy between the calculated relative Pacific-North American plate motion and estimates of slip rates on the San Andreas fault. Combined, these geodetic and relative plate motion rates suggest that other active faults in the western Transverse Ranges may accommodate additional shortening. High present day convergence rates across the channel (Larson, 1990), abundant tight folds, and recent seismicity including the 1978 M = 5.1 Santa Barbara earthquake (Fig. 1), suggest that the majority of the additional shortening may be accommodated by thrusting and reverse faulting along the Santa Barbara coastline.

Axial Surface Seismicity: "Folding Earthquakes ?"

Earthquakes have long been associated with the sudden release of stored elastic strain in rocks by slip on faults in the earth's crust and upper mantle. Modern theories of folding related to faulting in the brittle crust (e.g., Suppe, 1983) suggest that movement on non-planar thrust faults also causes deformation of the overriding hanging wall block. This deformation is localized along active axial surfaces related to bends in the underlying faults (Fig. 3). Folds grow as material moves through these active axial surfaces predominantly by bedding parallel slip. A recent earthquake swarm in the Santa Barbara Channel of southern California along the active axial surface of the Offshore Oak Ridge trend (Fig. 3A) indicates that folding, as well as faulting, may occur seismically. This axial surface seismicity, (or folding earthquakes), may provide insight into the location and types of underlying faults and locate segment boundaries for damaging earthquakes on the underlying causative fault systems.

Between April 20-25 of 1984, a swarm of over 400 earthquakes (M= 0.5 - 4.0) occurred roughly 30 km south of the city of Santa Barbara along the Offshore Oak Ridge trend (Fig. 3A). The events were recorded by the U.S.C. network which included ocean bottom seismometers. Shaw and Suppe (1991) and Shaw et al. (1992) have interpreted the Offshore Oak Ridge trend as an active axial surfaces that folds strata above a thrust ramp in the Deep Channel fault. The hypocentral locations of the seismicity define a steeply dipping plane (Henyey and Teng, 1985) along the active axial surface (A); (Fig. 3B). Preferred nodal planes from single event and composite focal mechanisms (near horizontal and ≈ 20°N dipping); (Henyey and Teng, 1985) are consistent with folding by bedding plane slip through the active axial surface (A) (Fig. 3). The horizontal and ≈ 20°N dips of the preferred nodal planes are, however, inconsistent with a near vertical through-going fault. Continuous and coherent seismic reflections in profiles across the trend also preclude active near surface faulting. These focal mechanism solutions and the spatial association of the swarm with the mapped axial surface suggest that the hypocenters outline the extension to depth of the active axial surface (A) of the Offshore Oak Ridge trend. The depth of the seismicity along the axial surface indicates that the Deep Channel fault ramps upward from at least 16.5 km beneath the offshore trend and approaches the seafloor south of Santa Cruz Island (Fig. 2).

References

DeMets, C. Gordon, R.G., Stein, S., and Argus, D.F., 1987, A revised estimate of Pacific-North America motion and implications for western North America plate boundary zone tectonics, Geophys. Res. Letters, V. 14, No. 9, p. 911- 914.

Henyey, T.L., and Teng, T., 1985, Seismic studies of the Dos Cuadras and Beta Offshore Oil Fields, Southern California OCS, A final technical report submitted to the Dept. of the Interior; Minerals Management Service, by the Center for Earth Sciences, USC, California.

Larson, K., 1990, Precision, accuracy, and tectonics from the Global Positioning System, doctoral dissertation, Univ. of Calif., San Diego.

Mount, V.S., 1989, State of Stress in California and a seismic structural analysis of the Perdido Fold Belt, Northwest Gulf of Mexico, Doctoral Thesis, Princeton University.

Shaw, J.H., and Suppe, J., 1991, Slip rates on active blind-thrust faults in the Santa Barbara Channel, Western Transverse Ranges Fold-and-Thrust Belt, A.G.U. Program and Abstracts, vol. 72, no. 44, p. 443.

Shaw, J.H., Bischke, R.E., and Suppe, J., 1992, Evaluation of the use of compressive growth structure in earthquake hazard assessment, NEHRP Technical Reports, v. XXXIII, U.S.G.S. Open-file Report 92-258, p. 619-622.

Suppe, J., 1983, Geometry and kinematics of fault-bend folding, Am. J. Sci., v. 283, p. 684-721.

Suppe, J., Bischke, R.E., and Shaw, J.H., 1991, Evaluation of the use of compressive growth structure in earthquake hazards assessment, NEHRP Technical Reports v. XXXII, U.S.G.S. Open-file Report 91-352, p. 192-195.

Suppe, J., Chou, G.T. and Hook, S.C., 1992, Rates of folding and faulting determined from growth strata, in *Thrust Tectonics*, K.R. McKlay ed., Unwin Hyaman, Publisher.

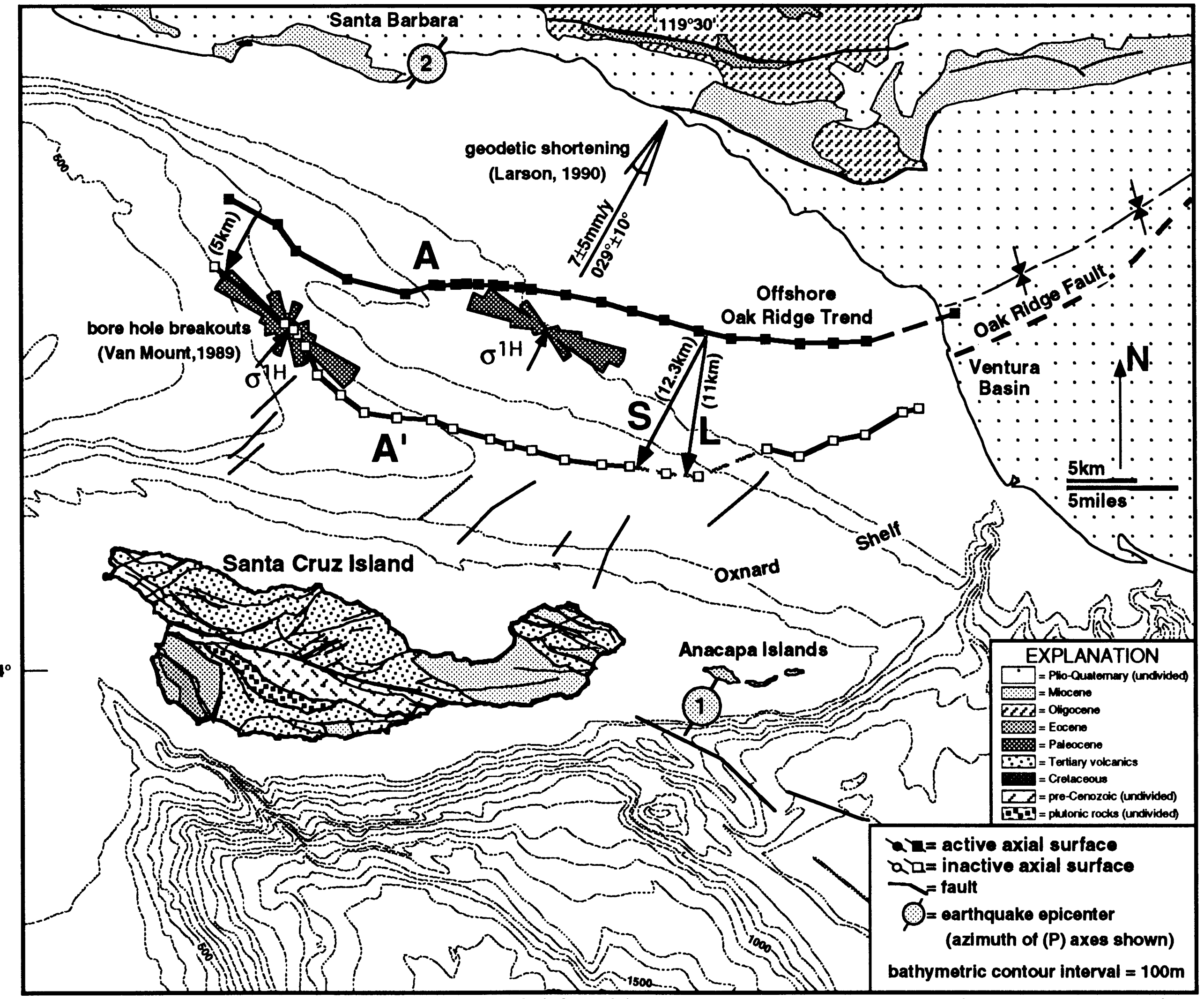

Figure 1: An axial surface map of the Offshore Oak Ridge kink band (A-A'). Sharp bends in the axial surfaces south of Santa Barbara suggest changes in subsurface geometry and slip on the underlying Deep Channel thrust (Fig. 2). A gradual decrease of the kink band width to the east without offset of the active axial surface (A) suggests a gradual change in slip, and not fault geometry, as the thrust approaches Ventura. Oblique, left-lateral thrusting (S=12.3km) on the underlying Deep Channel fault suggested by the axial surface map pattern is consistent with present day stress directions, tear fault orientations, earthquake P-axes, and the measured geodetic shortening direction. Fold limb length (L) equals fault dip-slip. σ1H = estimate of the trace of the maximum compressive stress that is perpendicular to borehole breakout directions. Epicenter (1) - 1978 M = 5.1 Santa Barbara earthquake; (2) 1973 Ml = 5.0 Anacapa earthquake.

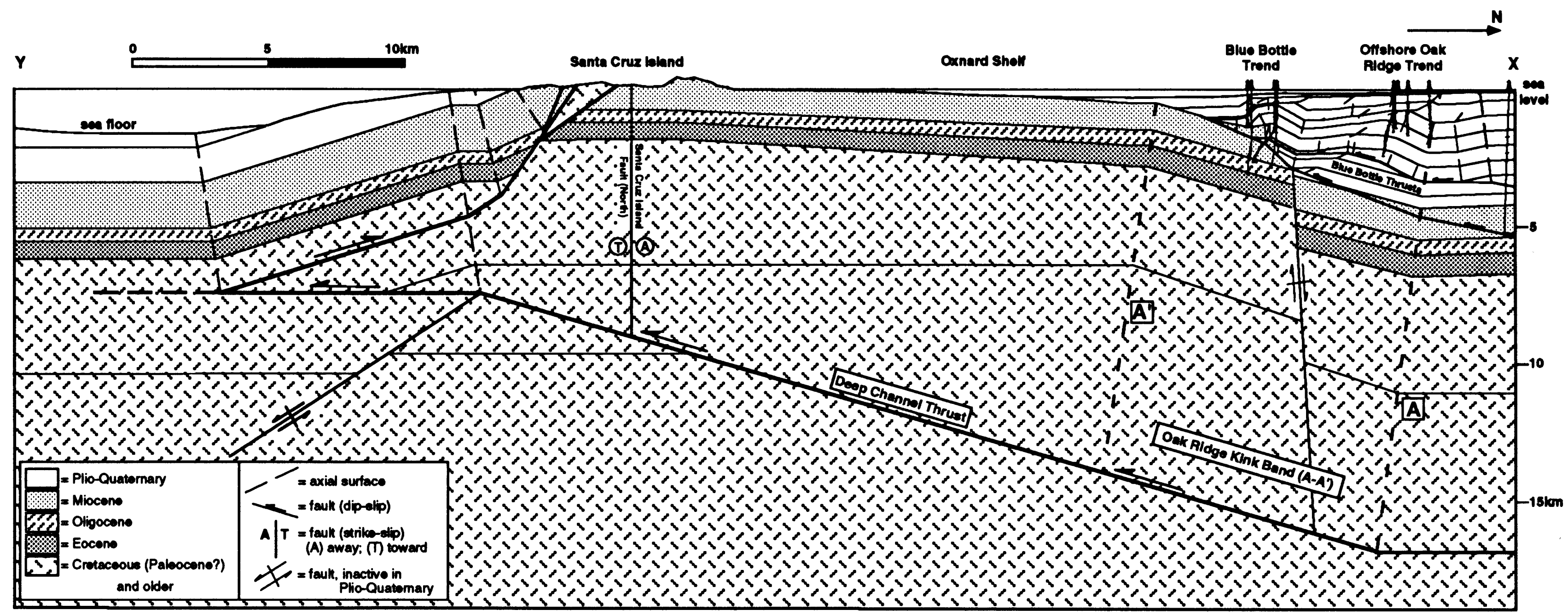

Figure 2: A preliminary, balanced regional cross section across the eastern Santa Barbara Channel constrained by subsurface seismic reflection and well log data. The Deep Channel thrust ramps beneath the Offshore Oak Ridge trend, and approaches the surface south of Santa Cruz Island. Slip may reach the surface along a number of south dipping reverse faults on the island. The kink band width (A-A') of the Offshore Oak Ridge trend (mapped in Fig. 1) represents dip-slip on the underlying fault. Shallower levels of faulting active along the Blue Bottle trend ramp from depth in the northern channel and beneath the Santa Barbara coastline (Fig. 1). The trace of the cross section is shown in Figure 3A.

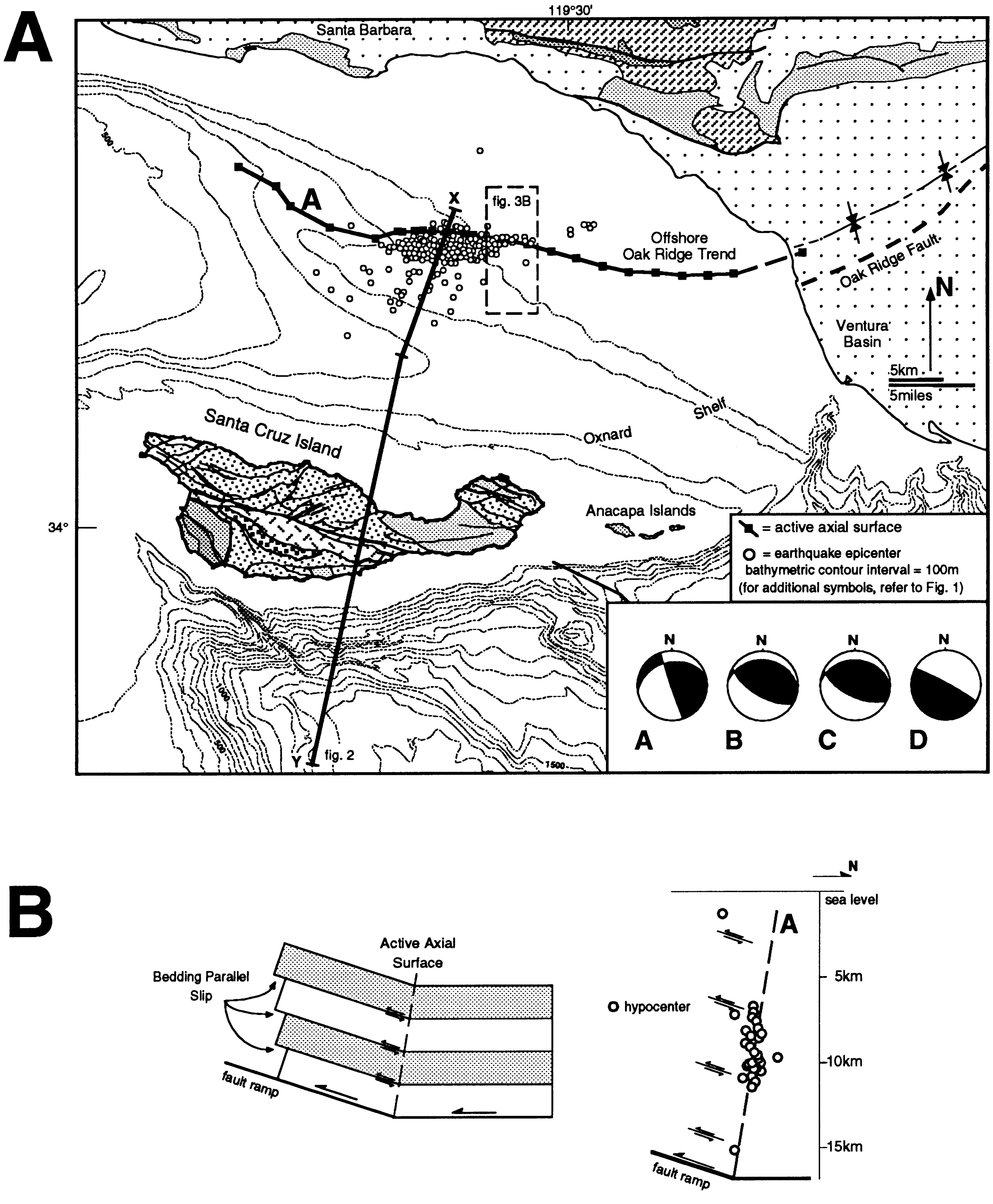

Figure 3A: Epicenters from an earthquake swarm in 1984 (Henyey and Teng, 1985) define the active axial surface (A) of the Offshore Oak Ridge trend. Single event (A, B) and composite (C, D) focal mechanism solutions from the 1984 seismicity show gentle north dipping (A, B, C) and horizontal (D) preferred nodal planes (Henyey and Teng, 1985) consistent with folding through the active axial surfaces by bedding parallel slip **3B**. The seismicity outlines the dipping active axial surface (A) (hypocenters from the dashed box on 3A are plotted). The depth of seismicity along trend suggests that the underlying thrust ramps from a depth of at least 16.5 km and nears the seafloor to the south of Santa Cruz Island (see Fig. 2). (X-Y) is the trace of the cross section in Figure 2.