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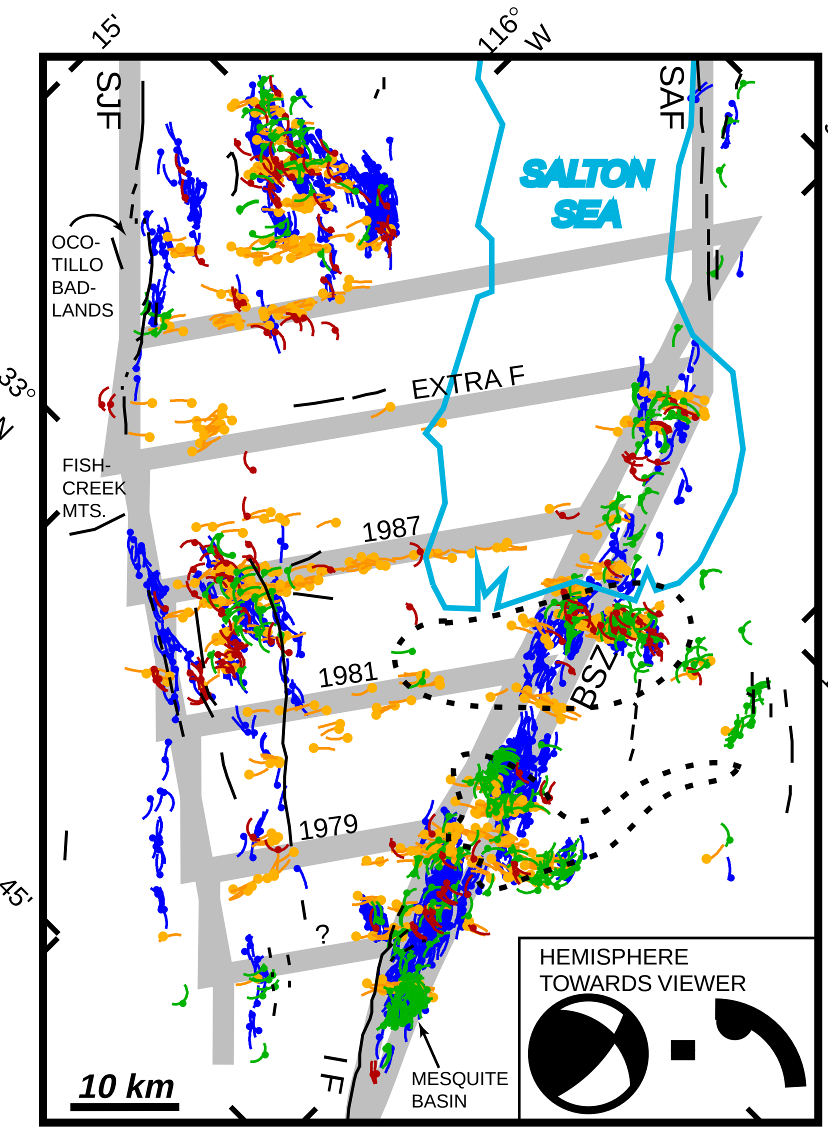
EARTHQUAKES, FAULTS, AND STRESS IN SOUTH CALIFORNIA
Leonardo Seeber and John G. Armbruster
Lamont-Doherty Earth Observatory, Palisades, NY 10964

In 1999, this project has progressed in four related topics, all in collaboration with other researchers. They are discussed in the order of our level of effort.

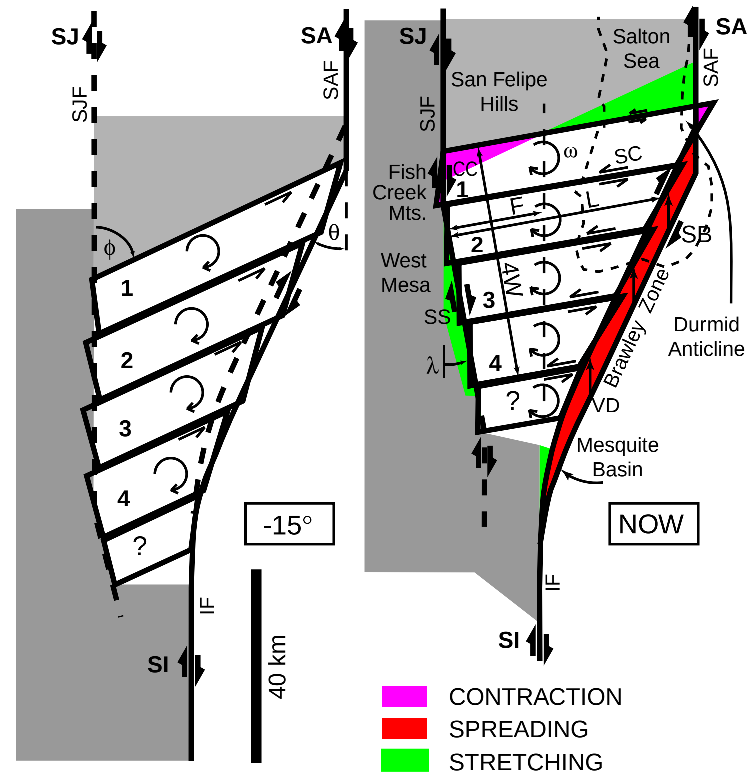
Continental Breakup in Southern California. The southern end of the San Andreas continental transform is marked by a gradual transition to the oceanic ridge-transform system in the Gulf of California, in one of the few examples of active continental breakup. A set of en-echelon transforms characterize the entire transtensional boundary, but the transitional portion is much broader and more complex than the mature oceanic portion, suggesting that the evolution from a continental to an oceanic regime involves a variety of structures and deformation mechanisms. The Salton Trough marks the northern and, presumably, the youngest and most continental portion of the transitional boundary. It is centered at the extensional jog between the Imperial and the San Andreas fault, but it is also associated with a wide range of other structures. The Plio-Quaternary evolution of the Salton Trough involves crustal stretching and thinning by east-dipping normal and detachment faults surfacing along the western border of the trough (Axen and Fletcher, 1999), extension and dextral translation by a set of parallel northeast-striking left-lateral cross faults rotating clockwise about vertical axes (Hudnut et al., 1989), and spreading by dike injection along the Brawley Seismic Zone marking the axis of the trough (Fuis et al, 1982). Our goal is to quantify the contributions from each of these mechanisms through the evolution of the trough.

We are constructing kinematic models of the Quaternary evolution of the Salton Trough by combining structural constraints from earthquakes (Figure 1) and temporal constraints from stratigraphy in collaboration with Becky Dorsey, University of Oregon. The border faults were active in the early Quaternary, but not later. Thus, one of the challenges is to account for the "extensional" jog without net crustal stretching in the current regime. An irrotational bifurcation of the Imperial fault into the San Andreas and the San Jacinto faults requires the latter to take up most of the motion and is therefore not permissible. In contrast, models that include a major component of clockwise rotation and formation of new crust at the Brawley zone (rifting) can account for the kinematics of the master faults feeding into the trough as well as for many secondary structures within it (Figure 2). For example, extension and compression are expected and geologically observed on the southwestern (San Felipe Hills) and northeastern (Salton Sea) sides of the trough.
The model allows for a maximum rotation rate of 0.4 μrad/yr. This end-member condition requires a transform-parallel spreading on the Brawley zone of 7mm/y. Clockwise rotation trades off with slip rate of the southern Coyote Creek fault. A significant slip rate on this fault implies a lower rotation and higher spreading rates. The model predicts a rapid increase in the spreading rate as the angle between the cross faults and the transform approaches 90°, suggesting that spreading along the Brawley zone is a recent development. The San Jacinto fault might have developed together with the rotation system. Preliminary age constraints from growth structures suggest rotation started about 1my ago. At the maximum rate allowed by the model, this age would account for 22° of clockwise rotation. This is probably an overestimate since significant slip has accumulated on the southern San Jacinto fault zone.

Structure provides strong constraints on fault kinematics in the evolution of the Salton Trough. Modeling this evolution will reveal tectonic processes in continental break up and in the development of passive margins. It will also provide scenarios for earthquake sequences that might involve the southern SAF. The Elmore Ranch cross fault rupture in 1987 triggered the Superstition Hills fault rupture a day later (Hudnut et al., 1989). Similarly, rupture of the Extra fault is expected to bring the southern San Andreas fault (SAF) closer to failure. Right-lateral slip and rifting on the Brawley zone will also contribute to loading the SAF, but more uniformly distributed in time.



gure 1. Focal mechanisms interpreted and represented as slip planes in the Salton Trough area. Color according to rake: red=reverse; blue=right-lateral green=normal; yellow=left-lateral (Armbruster and eeber, SCEC Data Center). Mapped faults are in black. Fault array modeled from these faults and from ismicity is in gray. Years of ruptures are indicated on the cross faults. Geothermal areas are dotted.



INVARIANT:
SI = SA+SJ = 36mm/y
θ =25°; W = 12.5km
$L_{1;2;3;4}$ =
= 53.6; 49.9; 36.7; 28.1km

TIME DEPENDENT:
SA = 26mm/y; SJ = 10mm/y
F1 = 23.0km; F4 = 16.3km
φ = 80°; λ = 10°
Unknowns: ω; SS_i; SB_i; VD

Figure 2. Kinematic model for the Salton Trough. The far-field slip rates on the Imperial (IF), San Andreas (SAF), and San Jacinto (SJF) faults, SI, SA, SJ, respectively, are accounted for by clockwise rotation (ω) of left-lateral cross faults (SC) and intervening blocks, by right latera faulting along the outer boundaries of the rotating domain (SB and SS), and by spreading on the Brawley zone (VD). Space adjustments including both extension and compression are needed locally, but no regional extension is necessary to accommodate the "extensional" jog between the IF and the SAF. In the version of the model displayed here, the accumulated displacement on the SJF and SAF are nearly the same, implying that slip rates on the SJF and on the SAF were higher and lower, correspondingly, in the early stages of the rotation episode. The modeling produces a range of permissible solutions that can be compared to observations.

A Major Rupture Sequence on the Northern Anatolia Continental Transform. In collaboration with David Okaya and Yehuda BenZion at USC and Andy Michael and Sue Hough at the USGS, we have been operating since late August 1999 a 10-station RAMP/IRIS network on the Karadere segment of the Northern Anatolia right-lateral transform (NAT) at the eastern end of the M7.8 120km-long rupture on August 17, 1999. Emergency funds for logistic support were provided by NSF. This effort was initially focused on fault-zone trapped waves, but the data we are collecting offer unique opportunities to investigate general properties of major continental transform, such as the SAF, and the scope of the project is now broadened, as follows.

Stress transfer and rupture nucleation. Our network resolves well seismicity in the nucleation area of the November 12 mainshock. This rupture started very near the end of the August 17 rupture and propagated east for about 40 km. A preliminary sample of about 1000 hypocenters shows that much of the seismicity is diffused on a number of secondary faults, but that a burst of seismicity illuminated the master fault in the two weeks prior to the Nov 12 mainshock. This shift in the pattern of small earthquakes may be indicative of a creep event precursory to the second mainshock. If this observation holds up, we might be able to ascribe the timing of the second mainshock to a stress rise caused by a regional strain event rather than to weakening of the causative fault by hypothetical processes at the future rupture nucleation. In general, high-resolution coverage of the sequence will permit tests of stress-transfer models.

Fault-Proximal Ground-Motion Characteristics. We have recorded on scale the M7.2 November 12 mainshock at eight sites ranging from 0.2 to 40 km from the rupture. Several of these sites were either on or close to the August 17 rupture trace. This data set will provide unique information ground-motion characteristics near major faults. Surprisingly, the largest acceleration was recorded on the fault at a site ≈10km from the rupture (Figure 3), not at the site 0.2 km from the rupture. The following hypotheses can be addressed by the data: (1) The master fault is weak in the upper several km of the crust and radiates little energy in this depth range. In support of this hypothesis, aftershocks are sharply limited below a depth of ≈5km; (2) Amplification and distortion of strong motion by non-linear response are associated with a wedge of mechanically and chemically damaged material associated with major faults; (3) Fault-zone trapped waves are important components of the strong motion near the trace of a major fault.

Slip-Distribution on the 1992 Landers Rupture from Changes in Regional seismicity. We have shown that the response of the far-field seismicity to the change in Coulomb stress from the 1992 Landers mainshock rupture can be modeled for the distribution of slip on that rupture. We have tested the robustness of the result by comparing a wide variety of inversion schemes. The solution space includes spiky and useless solutions. Useful results are consistently obtained if the iteration scheme includes strategies for favoring smooth distribution of slip over the rupture.

Pressure solution and active structure in the Ventura Basin

Jan Vermilye and Nano Seeber are collaborating on a study of pressure solution in the active fold-thrust belt associated with the San Cayetano fault in the Ventura basin. Seeber's 1999 contribution was covered by this grant, but the results are reported in connection with a proposal by Vermilye and Seeber to continue this work.

Recent and Expected Products and Publications

Armbruster and Seeber 1998, updated files of focal mechanisms and slip-planes for south California as well as a version of QKVIEW to visualize these data in SCEC data base.

Seeber L. and J.G. Armbruster, The San Andreas fault system through the Transverse Ranges as illuminated by earthquakes, J. of Geoph. Res., 100, pp. 8285-8310, 1995.

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Seeber L. and J.G. Armbruster, Earthquakes as beacons of stress change, re-submitted to Nature, November, 1999.

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Sorlien, C.C., L. Seeber , A.T. Scott Rapid subsidence and south propagation of a thrust wedge into the southern California borderland, AAPG Pacific Section, Annual Meeting, 1999.

Seeber L., J.G. Armbruster, D. Okaya, Y. BenZion, N. Field, and A.J. Michael, 4D Fault-zone properties of the Duzce branch of the North Anatolian fault system ruptured in the August 1999 Izmit, Turkey, earthquake, EOS 80, p.F648, 1999.

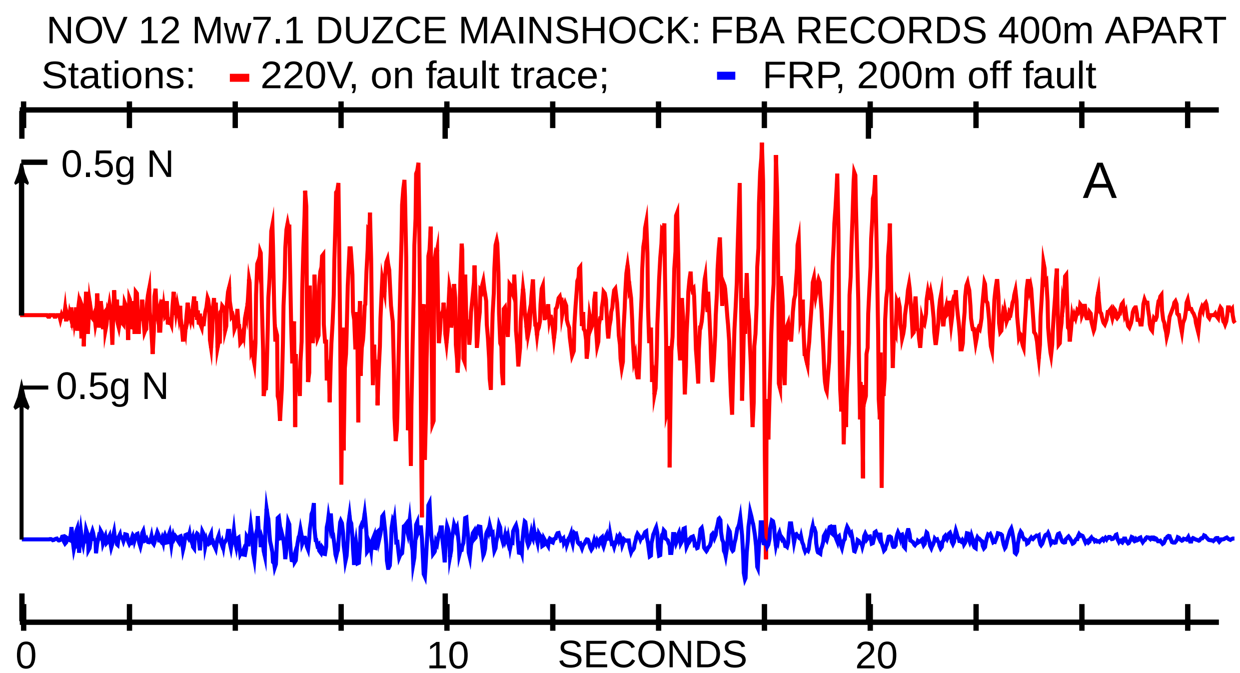
Dorsey , R.J., L. Seeber, M.S. Steckler, Stratigraphic constraints on a block-rotation model for the Salton Trough, Preliminary insights and hypotheses, EOS 80, p. F715, 1999.

Other References

Axen, G. J., and Fletcher, J. M., Late Miocene-Pleistocene extensional faulting, northern Gulf of California, Mexico, and Salton Trough, California, International Geology Review, 1999

Fuis, G.S. , W.D. Mooney, J.H. Healey, G.A.McMechan, and W.J. Lutter, 1982, Crustal structure in the Imperial Valley region, in The Imperial Valley, California, earthquake of October 15, 1979, U.S. Geological Surv. Prof. Pap. 1254, pp. 25-50.

Hudnut K.W., L. Seeber and J. Paceco, 1989, Cross-fault triggering in the November 1987 Superstition Hills earthquake sequence, southern California, Geophys. Res. Lett. 16, 199-202.



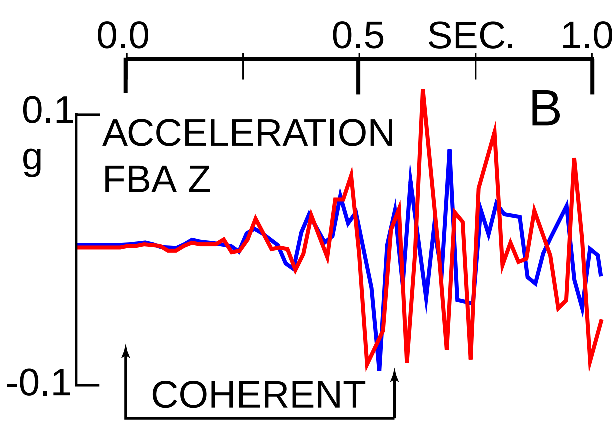


Figure 3. Comparison of strong motion of the November 12, 1999 M7.1 Duzce mainshock recorded by FBA at two nearby stations (≈400m) about 10km from that rupture. One station is on the fault trace that ruptured August 17 (220V) the other 200m from the trace (FRP). On the fault trace, the spectrum is shifted toward lower frequencies and N-S acceleration, which is almost normal to the strike of the fault, is about 5 times higher than off the fault (A). The difference is less for the E-W components which are nearly parallel to the strike of the fault. Finally, the first 0.6 seconds of the P waves on the vertical components are remarkably coherent (B). This coherence is comforting in terms of the fidelity of the records, and also suggests that the ground motion is amplified by near-surface characteristics of the fault at the recording site. Station 220V is located on a fault-parallel shutter ridge made up of weak faut-zone material.