Annual Report, 1999. Pressure solution deformation associated with faulting in southern California: Implications for the physics of fault slip and seismic hazard assessment

Jan M. Vermilye
Department of Earth & Environmental Science
Whittier College, Whittier, CA 90608

Leonardo Seeber
Lamont-Doherty Earth Observatory
Palisades, NY 10964

Introduction

The evaluation of seismic hazard requires reconciliation of measured strain and observed seismicity. Although most of the strain accumulated during interseismic periods is thought to be stored elastically (until released by seismic slip) a poorly known but significant portion of the total strain is accounted for by permanent aseismic deformation. This generally consists of diffuse deformation within the rock masses between faults. The permanent-to-elastic strain ratio is expected to depend on mechanical conditions, such as stress and strain rate, on rock properties that affect solubility and permeability, such as fracture density, and on factors affecting fluid flow such as depth and surface topography. Some of these factors may vary dramatically in space and time, especially in the aftermath of a large rupture. The very unusual conditions after a large earthquake may be at least in part responsible for concentrating aseismic strain near these ruptures in time and space.

Background

Deformation within the seismogenic crust is generally considered in terms of frictional processes and brittle deformation mechanisms. However, earthquakes and brittle failure occur at depths where strain is also accommodated by pressure solution, a non-brittle mechanism. Studies of exhumed mountain ranges have established pressure solution as an important mechanism, accounting for significant shortening strains within ancient contractional orogenic belts (e.g. Elliot, 1976; Wright and Platt, 1982; Wright and Henderson, 1992). Layer-parallel shortening early in the orogenic process is manifested by pervasive, grain-scale strain fabrics and spaced solution cleavage within the incipient thrust sheet (e.g. Protzman & Mitra, 1990; Dunne & Caldanaro, 1997). This early deformation is followed by cleavage associated with folding or faulting (e.g. Grey & Mitra, 1993; Carrio-Schaffhauser & Gaviglio, 1990; Grant, 1990).

Observations of pressure solution deformation in young, active tectonic settings are lacking. This leaves unanswered a number of questions about the timing, the rate, depth range, and the pervasiveness of pressure solution as a deformation mechanism in active deformation belts. Observations of pressure solution in active belts are particularly important for understanding the role that this mechanism may play in the earthquake cycle. Recent results indicate substantial aseismic, postseismic strain. This suggests that pressure solution may be particularly important during postseismic deformation. Postseismic deformation has been documented following the 1992 Landers and the 1994 Northridge earthquakes (Massonnett et al., 1996; Peltzer et al., 1996; Bock, et al., 1997). While it has been suggested that this deformation is driven by viscous flow in the lower crust or aseismic fault creep it may in part reflect accelerated rates of pressure solution due to fracturing and pore fluid flow.

Progress and Major Findings to Date

The San Cayetano is a seismically active fault located in the western Transverse Ranges. It is one of the fastest moving thrust faults in southern California. We examined pressure-solution structures along seven transects across the fault in order to evaluate the role that pressure solution plays in accommodating aseismic deformation. Four distinct components of pressure-solution controlled deformation are recognized:

1) Pervasive grain-scale deformation within the rock masses;
2) Shortening along cleavage planes;
3) Aseismic slip on faults;
4) Cobble interpenetration.

These classes of pressure solution structures may reflect processes taking place over distinct depth ranges, and/or distinct positions in the growing orogen (and therefore distinct times), and/or distinct phases of aseismic deformation during the earthquake cycle.

The observed structures represent both pre- and syn-faulting deformation. Distributed grain-scale shortening fabrics and solution cleavage accommodate shortening in the earliest stages of compression and in the most external portions of the orogenic belt, at the leading edge of the deforming wedge. Faulting and cobble interpenetration accommodate syn-faulting deformation. Faulting, both cataclastic and solution-precipitation faulting, predominates in the later stages of the deformation process. Within several hundred meters of the San Cayetano fault, the density of mesoscopic (outcrop scale) faults increases. The larger of these faults with accumulated displacements on the order of several-meters are typically associated with gouge and may be seismogenic. In contrast the smaller of these faults with displacements on the order of mm to cm lack gouge and are associated with mineral growth on the slip surfaces. Pressure-solution slip on these faults may be enhanced by a combination of fluid flow, pore pressures, and shear stress near the San Cayetano fault. These properties are expected to vary substantially during earthquake cycles characterized by large ruptures.

Early grain-scale dissolution strain accommodates from 9-23% shortening with no observed depth control on the magnitude of shortening (Meyer, 1999). These values represent minimum aseismic strain because additional strain is taken up by removal of material on cleavage planes. Strains as high as 50% have been ascribed to cleavage formation in other orogens. Assuming an onset of north-south directed compression in the Ventura Basin at 4 ma and initiation of slip on the San Cayetano fault at 1 ma (Huftile & Yeates, 1996) grain-scale shortening rates are between 1 and 2 mm/yr. Similar rates may presently be affecting the external wedge within the LA Basin accommodating a portion of the estimated 5-7 mm/yr contraction.

Pressure-solution slip on the small faults accommodates 2-8% shortening and cobble interpenetration 1-9%shortening. Incomplete distribution data for these data preclude computation of shortening rates. The shortening directions ascribed to grain-scale fabrics, spaced solution cleavage, small faults (Fig. 1) and cobble interpenetrations are N-S to NE-SW (Fig. 2). These orientations are generally consistent with the current directions of stress and strain from earthquake and geodetic data. The data also suggest systematic differences in shortening directions among the three solution-controlled mechanisms in some of the areas sampled. These differences can be interpreted as a rotation of the stress field or a rotation of the rock through an invariant stress direction during the ongoing compressive phase of the Transverse Ranges orogen.

Pressure-solution strain detracts from the elastic strain energy budget and decreases the hazard from earthquakes. In addition to this first-order effect, pressure-solution strain is probably coupled with other deformation processes such as fault-related folding, fault growth, and the stress/strain cycle along large seismogenic faults. Pressure solution strain may retard the rise in stress during the interseismic period. The ratio between permanent and elastic strain may vary drastically during this cycle. Understanding how pressure solution affects the coupling between stress and strain may be critical in the interpretation of geodetic deformation in terms of loading of seismogenic faults.

References

Bock, Y., and 20 others, 1997, Southern California permanent GPS geodetic array: Continuous measurements of regional crustal deformation between the 1992 Landers and 1994 Northridge earthquakes, *J. of Geophys. Res.*, 102, 18013-18033.

Carrio-Schaffhauser, E. & Gaviglio, P, 1990, Pressure solution and cementation stimulated by faulting in limestones, *J. Struct. Geol.*, 12, 8, 987-994.

Duebendorfer, E.M., Vermilye, J.M., Geiser, P.A. & Davis, T.L., 1998, Evidence for Aseismic Deformation in the western Transverse Ranges, southern California: Implications for seismic risk assessment, *Geology,* 26, 3, 271-274.

Dunne, W.M. & Caldanaro, A. J. Jr., 1997, Evolution of solution structures in a deformed quartz arenite: geometric changes related to permeability changes, *J. Struct. Geol.,* 19, 5, 663-672.

Elliot, D., 1976, The energy balance and deformation mechanisms of thrust sheets, *Phil. Traans. R. Soc. Lond*. A. 283, 289-312.

Grant, N.T., 1990, Episodic discrete and distributed deformation: consequences and controls in a thrust culmination from the central Pyrenees, *J. Struct. Geol.*, 12, 7835-850.

Gratier, J. P., 1983, Estimation of volume changes by comparative chemical analyses jn heterogeneously deformed rocks (folds with mass transfer), *J. Struct. Geol.,* 5, 3/4, 329-339.

Grey, M.B. & Mitra, G., 1993, Migration of deformation fronts during progressive deformation: evidence from detailed structural studies in the Pennsylvania Anthracite region, U.S.A., *J. Struct. Geol.*, 15, 3- 5, 435-449.

Huftile, G.J. & Yeates, R.S., 1996, Deformation rates across the Placerita (Northridge M_W=6.7 aftershock zone) and Hopper Canyon segments of the Western Transverse Ranges deformation belt, *Bulletin of the Seismological Society of America*, 86, 1B, S3-S18.

Massonnet, D., Thatcher, W., & Vadon, H., 1996, Detection of postseismic fault-zone collapse following the Landers earthquake, *Nature*, 382, 612-616.

Meyer, K.L., 1999. Pressure solution as an aseismic deformation mechanism, Piru Creek-Lake Piru: western Transverse Ranges, California, *Masters Thesis*, Northern Arizona University.

Peltzer, G., Rosen, P., Rogez, F., & Hudnut, K., 1996, Postseismic rebound in fault step-overs caused by pore fluid flow, *Science*, 273, 1202-1204.

Protzman, G.M. & Mitra, G., 1990, Strain fabric associated with the Meade thrust sheet: implications for cross-section balancing, *J. Struct. Geol.*, 12, 4, 403-417.

Wright, T.O. & Henderson, J.R., 1992, Volume loss during cleavage formation in the Meguma Group, Nova Scotia, Canada, *J. Struct. Geol.*, 14, 281-290.

Wright, T.O. & Platt, L.B., 1982, Pressure solution and cleavage in the Martinsburg Shale, *American Journal of Science*, 282, 122-135.

Publications resulting from research

Meyer, K.L., 1999. Pressure solution as an aseismic deformation mechanism, Piru Creek-Lake Piru: western Transverse Ranges, California, *Masters Thesis*, Northern Arizona University.

Vermilye, J.M. & Seeber, L., 1999. Pressure solution in the San Cayetano fault zone: Implications for strain accommodation and seismic risk, *Geol. Soc. Am. Abstr. Programs*, 31, A376.

Vermilye, J.M. & Seeber, L., 1999. Pressure solution deformation associated with active faulting in southern California: The San Cayetano fault, In preparation for submission to The Journal of Structural Geology.

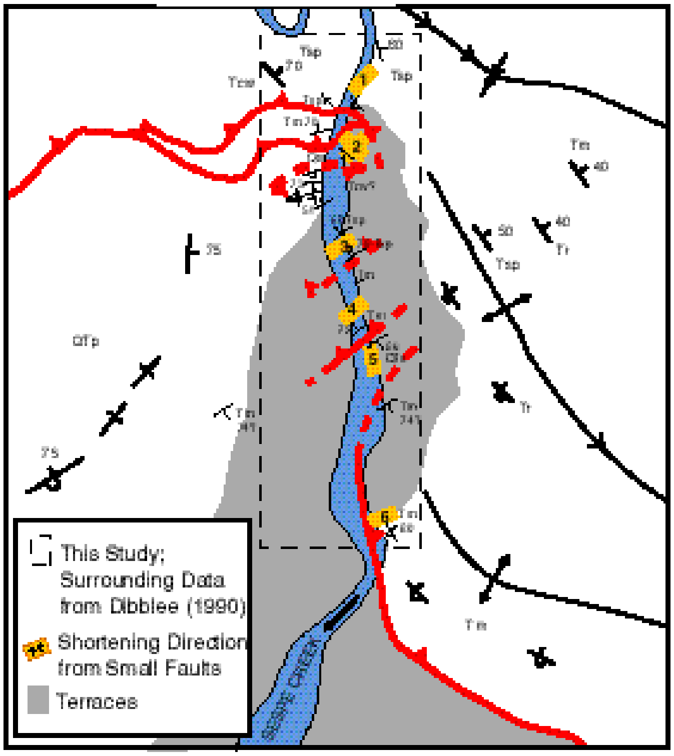

Fig. 1. Shortening directions from small faults and mapped structure along Sespe Creek.

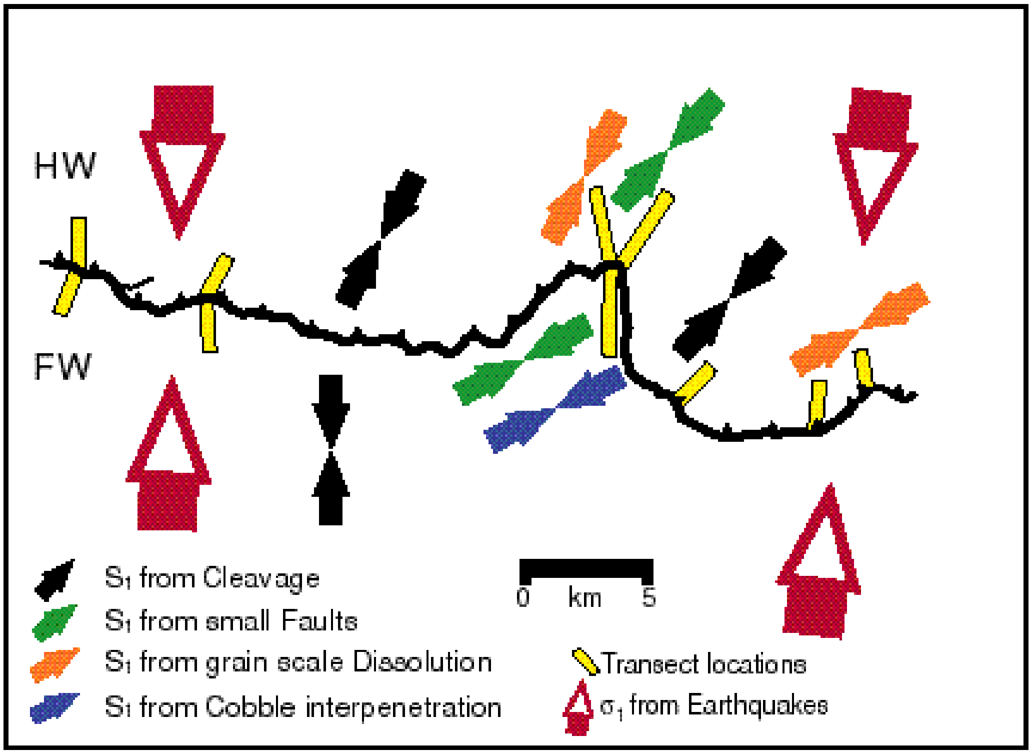

Fig. 2 Stress (σ) and strain (S) associated with the San Cayetano fault zone. The maximum horizontal shortening directions for pressure solution shortening structures and maximum horizontal compressive stress from earthquakes.