# 1999 Progress Report:
# Characterizing Seismogenic Sources Associated with the Uplift of the San Bernardino Mountains

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One of the foremost components of SCEC's scientific mission is the characterization of potential earthquake sources that threaten the safety and economy of southern California. This civic duty has driven many valuable studies of seismogenic structures in the Los Angeles basin, but the rupture potential of many faults in the encompassing Inland Empire remain unquantified. In addition, the more fundamental pursuit of understanding fault behavior is somewhat stymied in metropolitan Los Angeles, by the lack of exposure due to urban development and a prevalence of blind structures. To intelligently assess earthquake hazards in complexly faulted regions, we must build our understanding of interacting fault systems where exposure is complete and paleoseismic histories are manifest as ruptures in surficial sediments (rather than folding at depth).

The tectonic structure of the Los Angeles region consists of a complex coalescence of Transverse Ranges-style reverse faulting on the north and Peninsular Ranges-style dextral faulting on the south (Fig. 1). The right lateral Newport-Inglewood, Whittier-Elsinore, and San Jacinto faults feed slip into Los Angeles from the south, which is somehow transferred to the transrotating (clockwise-sinistral) fold-thrust belt within the San Gabriel and Santa Monica Mountains to the north. These complex fault systems merge in Los Angeles, but the kinematics and dynamics of their interaction are not well known. As a result, there is no guide to predict how faults might behave in the future. For example, would a rupture of one of the strike-slip faults impose failure of one of the thrusts (or vice versa)? Are "doomsday" scenarios valid, in which most of the interacting elements fail successively over a very short period? Will great earthquakes occur along Los Angeles thrusts, or will they be limited to patchwork-failure due to segmentation by strike-slip faults? A better general understanding of how complex fault systems interact might help assess these possibilities in Los Angeles.

An analogous structural setting exists on the opposite side of the San Andreas fault, where the distributed dextral shear of the Eastern California shear zone meets a thrust belt along the northern margin of the San Bernardino Mountains (SBMs). Right-lateral faults, such as the Helendale and Lenwood, approach the impressive range front from the north with a fraction of the ~1 cm/yr dextral slip carried by the Mojave shear zone (Sauber et al., 1994) (Fig. 2). At the range front, however, their traces are perturbed by the North Frontal thrust system (NFTS), a complex array of south-dipping thrust segments and folds that have largely been responsible for uplift of the SBMs in the past 2 Myr (Spotila, 1998; Meisling and Weldon, 1989; May and Repenning, 1982). South of this thrust belt, a second series of dextral faults occurs within the Big Bear plateau (hanging-wall block) that are more or less along-trend from the faults to the north (Fig. 2). Although these two sets of strike-slip faults cannot be directly connected and do not clearly offset the NFTS, they do appear to disrupt its trace by causing excessive folding, sinuosity, and high-angle faulting (e.g. Blackhawk fault) within its zone (Sadler, 1982; Miller, 1987). Geologic common sense implies that intersecting fault systems can only exist if one has preceded the other, but the mutual perturbation and common evidence for late Pleistocene motion of both systems in the SBMs imply that they have been coactive. In addition, both the northern and southern set of right-lateral faults display evidence for large total displacements (~5-10 km) that would have required several million years to accrue, given typical slip rates for the Eastern California shear zone (Dokka and Travis, 1990). It may thus be required that the shear zone and thrust belt have been interacting in a complex fashion throughout the past 2 Myr history of uplift of the SBMs.

By characterizing the interaction of these two fault systems, a fundamental understanding of how strike-slip and thrust faults interact may be attained. To fully accomplish this, the spatial kinematics of the two systems need to be defined. Some of the strike-slip faults appear to bend into the thrust zone and rollover, for example, while the presence of strike-slip faults in the hanging wall implies that dextral shear continues to the south. Detailed fault mapping could indicate how these systems intersect and deform each other and how they can possibly remain active at the same time. In addition, the temporal kinematics of these two systems must be defined. Paleoseismic investigations of the strike-slip faults have revealed that they typically fail in large clusters of events that repeat every ~5 Ka (Rockwell et al., in prep.). The NFTS may have large rupture events that occur on this same timescale, have series of ruptures of small thrust patches between the strike-slip faults during these clusters (i.e. pairing), or show no relationship to the timing of strike-slip faults at all. If the recent activity along the NFTS can be determined, this structural system will serve as a good experiment of how such fault systems (i.e. analogous to Los Angeles) behave.

The NFTS might also pose a major threat to the growing population of the nearby mountain and desert communities and the dense population of the San Bernardino Valley. If the thrust ruptured in a single event, it would likely have ~3 m of throw (extrapolated for its 80-km-length [Wells and Coppersmith, 1994]), corresponding to a Mw=7.5 earthquake (based on 30-km-width [Spotila, 1998] and $\mu=3\times10^{11}$ dyne $cm^{-2}$). Such an event could repeat at intervals as short as ~5000 years (based on the largest estimate of recent uplift rate, see below) and would be as large as events feared in metropolitan Los Angeles (Dolan et al., 1995). Given the extent of damage of the M=6.5 Big Bear earthquake, a M7+ event on the NFTS would be truly serious and the danger of such an earthquake occurring needs to be defined. However, this structure has not been included in SCEC's hazard models (Phase II, 1994), due to the lack of data on its earthquake history (i.e. "type C region").

Previous investigations of the NFTS have been significant, but do not answer the above questions about its interaction with the Eastern California shear zone. Several studies have proposed that the NFTS has been decelerating since the middle Pleistocene, on the basis of how much lower recent uplift rates may be than the long-term uplift rate of the Big Bear plateau (Meisling and Weldon, 1989; Sadler, 1982). Given its total vertical displacement of ~1.6 km (Spotila, 1998), its longterm uplift rate has been ~0.8 mm/yr (since ~2 Ma). Late Pleistocene scarps, however, indicate recent vertical rates of 0.05-0.3 mm/yr (25 m-high, 0.5 Myr-old scarps [Meisling and Weldon, 1989]; 36-70 m-high, 0.4 Myr-old scarps [Meisling, 1984]; or 40 m-high, 130 Kyr-old scarps [Bryant, 1986]; ages based on soil chronosequences). Regardless of the estimate, the NFTS has thus slowed in the late Pleistocene. This range in uplift rate, however, shows that the degree of recent activity along the thrust system is not well known. The timing of its most recent rupture is also unconstrained. Most of the NFTS fails to exhibit Holocene ground rupture (Bryant, 1986; Miller, 1987), but paleoseismic investigations have not yet determined just when it last failed (e.g. Meisling, 1984). Moderate thrust-mechanism earthquakes have been attributed to the NFTS (e.g. Feigl et al., 1995), indicating that it is active to at least some degree, but more research is required to address the issues at hand.

Investigation of the recent history of rupture along the NFTS thus seems warranted, as it will address fundamental issues of fault behavior that are analogous to Los Angeles tectonics and is a worthwhile hazard study in its own right. To address both issues, the degree of recent activity along the NFTS must be quantified. In my Research Proposal for 1999, I describe plans to determine both the recent slip rate along the thrust system and the timing of its most recent rupture events. This will address the question of whether the thrust and strike-slip fault systems are coactive, test whether the clustered ruptures along the northern dextral faults are temporally related to rupture of the thrust fault in the past 10-20 Ka, and quantify the seismogenic potential (i.e. M7+ earthquakes) of this major southern California thrust fault. In addition to the proposed research, however, efforts of the past year have also advanced our knowledge of the NFTS. The results and implications of my SCEC-sponsored research in 1998 are summarized briefly below.

In the past year, significant advances have been made in our knowledge of the NFTS. During the completion of my Ph.D. thesis at Caltech with Kerry Sieh, I worked to attain an understanding of the relationship between transpressive motion along the San Andreas fault and orogeny in the SBMs (Spotila, 1998). To relate these two processes, I focused on constraining the kinematics and architecture of structures producing the vertical deformation. The NFTS has been responsible for the majority of uplift, yet its geometry, history, and relationship to the San Andreas fault had only been partly constrained (Li et al., 1992; Meisling and Weldon, 1989; Dibblee, 1975). To learn more, I documented a new geologic data set that constrained the pattern of vertical deformation across the entire hanging wall of the NFTS. By constraining the pattern of structural relief, I also hoped to constrain the distribution of plate motion accommodated in the SBMs and to use this to test hypotheses for what has driven the transpressive uplift and how strike-slip and orogeny relate.

The necessary constraints on the neotectonics of the thrust system and resulting mountain system came from a somewhat unorthodox data set. Because the range consists primarily of crystalline rock, no structural datum existed with the resolution necessary for learning about the fault geometry or displacement. A previously recognized, weathered erosion surface (Oberlander, 1972; Meisling, 1984), however, proved useful after detailed investigation of its origins. The weathered surface likely required millions of years to develop and is locally overlain by Miocene units, implying that where it is preserved atop the SBMs it indicates a lack of syn-uplift erosion. The weathered surface also probably had very low relief prior to initiation of the NFTS and other young structures, implying that rock uplift can be reconstructed from its present distribution.

The weathered surface thus restores the present topography of the Big Bear plateau and San Gorgonio block of the SBMs to as they'd be had no erosion occurred during the past few million years of uplift. The structure contours to this surface atop the hanging wall and footwall (Mojave Desert, Santa Ana Valley; based on borehole and geophysical data) are shown in Fig. 3. From this, calculation of the vertical displacement along bounding faults is straight-forward. The resulting displacement plot for the near-surface NFTS shows a somewhat-symmetric, bell-shaped curve that rises from zero uplift on east and west and reaches a maximum of vertical displacement (1.6 km) near the center (Fig. 4). This measurement of rock uplift implies an average rate of 0.8 mm/yr (since 2 Ma).

Structure contours of the weathered surface provide some constraint on the geometry of faulting at depth. With an assumed pre-faulting topography and the restored structural relief from the weathered surface, the down-dip shape of the NFTS can be modeled. Variations in uplift magnitude of the hanging wall can be attributed to dip changes on the underlying thrust when the horizontal motion is uniform down-dip. Increases in rock uplift are related to local steepening of the thrust plane, whereas small troughs in uplift are due to local flattening. This analysis was completed in cross sections and showed that NFTS may have a complex geometry, flattening under the structurally low Santa Ana Valley and steepening under the high San Gorgonio block (e.g. Fig. 5). The resulting fault geometry has a complex corkscrew appearance, steepening more on the east and flattening more on the west (Fig. 6). This non-unique analysis also shows that the NFTS can extend beneath and explain the relief of the entire Big Bear and San Gorgonio blocks. The NFTS thus appears to be a very large structure (>30 km width) and is likely responsible for raising most of the SBMs.

The weathered surface also constrains the magnitude and pattern of rock uplift across the central and northern SBMs. Coupled with constraints from thermochronometry (Spotila et al., 1998), the pattern of structural relief shows how horizontal plate motion has been accommodated through growth of the range. By simple mass-balance, the excess volume of rock uplift can be used to create an imaginary topographic surface, from which the north-south horizontal shortening can be derived as the change in line-length from a previous, approximately flat topography. The result indicates that as much as 6.3 km of north-south shortening has been accommodated by uplift of the SBMs and that shortening varies along a bell-shaped curve from east to west (Fig. 7). The peak convergence is coincident with the location of the 15-km-wide restraining bend along the San Andreas fault at San Gorgonio Pass (Fig. 1), implying the small geometric complexity along the transform system has resulted in a significant component of strike-slip motion being transformed into uplift of a major mountain range.

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