Fault interaction at the junction of the Transverse Ranges and Eastern California shear zone: a case study of intersecting faults

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Abstract

A case study from southern California illustrates the value of detailed geologic data for understanding the kinematics of complex fault systems. The neotectonic behavior of faults at the junction of the Eastern California shear zone (ECSZ) and Transverse Ranges has implications for the interaction of intersecting, segmented fault systems and regional plate boundary evolution. Paleoseismic observations indicate that the North Frontal thrust system (NFTS) has ruptured once in the Holocene with 1.7-m displacement, despite previous speculations of inactivity based on its dissection by younger strike-slip faults. Simple polyphase deformation, in which dextral shear has replaced and overprinted thrusting, is thus not a valid explanation for this system of intersecting faults. This illustrates the limitations of inferring rupture behavior from mapped fault patterns alone. Neotectonic and geomorphic observations along the thrust system also suggest that the thrust segment west of the intersection with the dextral Helendale fault is significantly more active than the segment to the east. This is consistent with a simple block velocity model, in which dextral slip on the Helendale fault is balanced by convergence on the western thrust segment, dextral motion on the poorly studied Pipes Creek fault to the southeast, and inactivity on the eastern thrust segment. This divides the San Bernardino Mountains into domains dominated by thrusting (west) and strike-slip (east), the union of which is a quasi-stable triple junction. We speculate that this union has migrated to the west as the Mojave Desert has been translated southwards along the San Andreas fault.

Keywords: Eastern California shear zone; Transverse Ranges; Faults

1. Introduction

Complex fault systems are a common mechanism of accommodating plate motion within the continental lithosphere (Molnar, 1988). Suites of intersecting, conjoined, and otherwise spatially associated faults can represent quasi-stable, least-work means of yielding to distributed strain (e.g., Jackson and McKenzie, 1994; Nur et al., 1993). As a result, the kinematics of active continental deformation can be perplexing and associated seismicity patterns difficult to forecast. Understanding the interaction of such complex fault systems, with respect to the long-term evolution of plate boundaries and the dynamic behavior of rupture cycles, is an important challenge.
Faults may be spatially associated and interact in a variety of ways, such as conjugate fault pairs, faults produced by slip partitioning, and secondary faults at bends or stepovers (Fig. 1). Such fault systems interact dynamically and can result in complex rupture patterns (Segall and Pollard, 1980; Philip and Meghraoui, 1983; Hudnut et al., 1989). Fault unions and intersections are particularly important for rupture mechanics, because they can act as segment boundaries that sometimes control rupture dimension (e.g., Sharp et al., 1982; Barka and Kadinsky-Cade, 1988; Harris and Day, 1993; Magistrale and Day, 1999). What will act as a segment boundary can be hard to predict until observed in an actual earthquake event (Sieh et al., 1993; Rubin, 1996). Complex groupings of faults also occur when deformation patterns are overprinted or represent transient “snap-shots” of fault evolution, such as within nascent shear zones or in response to changing plate boundary conditions (Wilcox et al., 1973; Tchalenko, 1970; King and Yielding, 1984). This also occurs on short time scales, such as the dynamic interaction of individual faults during rupture sequences (Wald and Heaton, 1994; Spotila and Sieh, 1995; Harris and Day, 1999). Fault groupings can often be so complex as to seemingly violate simple rules of fault mechanics or to require unusual arrangements of principal stresses (Anderson, 1905), such as with intersecting faults that form quadruple junctions (Fig. 2). Alternatively, these fault sets may represent polyphase deformation, in which active faults cut previous generations of structures. Mapped patterns of cross-cutting relationships between faults might even be indicative of what structures are inactive. In most cases, however, existing geologic data do not contain the completeness required for kinematic interpretation of how such complex fault systems evolve and dynamically interact.

In this paper, we explore the interactions of intersecting faults from a location where ample preexisting data help to define fault behavior. The Transverse Ranges of southern California provide examples of interacting faults at several levels (Fig. 2c). This system of convergent deformation occurs on both sides of the southern San Andreas fault that is oblique to plate motion (the “big bend”), creating a complex intersection near San Bernardino (Blythe et al., 2002). The fold and thrust belt of the western Transverse Ranges is, in turn, abutted by strike-slip faults that are parallel to the San Andreas fault, including the Whittier–Elsinore, Newport Inglewood, and San Jacinto faults (Tsutsumi et al., 2001). These fault confluences create mechanical problems that render the forecasting of rupture scenarios dubious (Dolan et al., 1995). To the east in the southern Mojave Desert, the North Frontal thrust system (NFTS) is intersected by fault strands of the Eastern California shear zone (ECSZ) (Dibblee, 1975). We have focused on this region because the intersection of these fault systems creates quadruple junctions that may interact in a complex dynamic fashion or may be the result of polyphase deformation. By documenting fault activity using geomorphic and paleoseismic observations, we test whether mapped fault patterns are actually indicative of active deformation and in turn explore the recent dynamic evolution of these fault systems.
interaction and long-term evolution of two complex fault systems.

2. The North Frontal thrust system and Eastern California shear zone

The NFTS occurs along the northern range front of the San Bernardino Mountains and has been largely responsible for uplift of the Big Bear plateau over the past few Myr (Dibblee, 1975; Meisling and Weldon, 1989; Spotila and Sieh, 2000). The 80-km-long thrust system is complex, consisting of discontinuous, over-
rate over the past 2–3 Ma has been >0.5 mm/year (Spotila and Sieh, 2000). In contrast, uplift rates based on soil—chronosequence age estimates of late Pleistocene (<0.5 Ma) alluvium in 25- to 70-m-high scarps are much slower, ranging from 0.05 to 0.3 mm/year (Meisling, 1984; Bryant, 1986; Meisling and Weldon, 1989). Thus, the NFTS has decelerated and may even have even become inactive.

The southernmost ECSZ is a broad array of discontinuous right-lateral faults that are sub-parallel to the San Andreas fault and have been active for at least the past few million years (Savage et al., 1990; Dokka and Travis, 1990a). It initiates near the restraining bend at San Gorgonio Pass and continues north for ~1000 km to interact with the Basin and Range. The ECSZ accounts for about 11–14 mm/year dextral shear, or ~25% of the relative motion between North America and the Pacific plate (Miller et al., 2001). Slip rates on individual faults in the zone are generally undocumented, but would be ~1 mm/year if slip is equally distributed from west to east across the dozen or so parallel fault strands (e.g., Houser and Rockwell, 1996). Earthquake recurrence times for these faults average several thousand years (Rockwell et al., 2000). Nonetheless, the ECSZ has produced significant earthquakes in the last several decades (Sieh et al., 1993; Fialko et al., 2001). The western limit of the southern ECSZ is defined by the Helendale fault, one of the more continuous strands. This fault bisects the NFTS into segments; a western branch unbroken by the shear zone and an eastern branch within the shear zone (Fig. 3). The eastern segment is intersected and abutted by several other dextral faults (e.g., Old Woman Springs and Lenwood faults). Neither the Helendale fault nor the other dextral faults have experienced historical rupture, but paleoseismic investigations of dextral faults north of the NFTS have demonstrated that they have been

Fig. 3. Fault map of the San Bernardino Mountains region, showing the intersection of the NFTS and Helendale fault. Numerous strike-slip faults of the ECSZ occur in both the hangingwall and footwall of the eastern thrust system. Focal mechanisms are shown for the 1992 Landers (a) and Big Bear earthquakes (b), as well as a 1992 aftershock with a thrust mechanism that probably occurred on the thrust (Feigl et al., 1995) (c). Earthquakes of M>4 with focal mechanisms consistent with dextral motion on northwest trending planes are shown as filled squares (1983–6/28/92), open circles (6/28/92–11/27/92), and filled circles (11/27/92–2/16/02) (Jones and Hough, 1995).
active in the Holocene and have earthquake recurrence times of several thousand years (Bryan and Rockwell, 1995; Houser and Rockwell, 1996). The degree of recent activity along the ECSZ and the apparent lack of Holocene motion along the NFTS point to the possibility that the dextral system has replaced and rendered inactive the thrust system (Sadler, 1982; Meisling and Weldon, 1989). This would make their intersection a cross-cutting relationship between older and younger fault sets. In this case, the $M=5.4$ earthquake in 1992 would represent a local fault patch triggered during an aftershock sequence, not indicative of major through-going activity on the entire NFTS. This “cross-cut” model fits with the younger geomorphic expression of the strike-slip faults and recent seismicity that has been dominated by strike-slip mechanisms. The 1992 $M=6.5$ Big Bear sequence was produced by rupture of short conjugate strike-slip faults (Jones and Hough, 1995). Subsequent to this sequence there have been numerous dextral events of $M>4$ throughout the San Bernardino Mountains, particularly between the San Andreas fault and the Big Bear epicenter (Fig. 3). These coincide with short, northwest trending fault strands, such as the Dollar Lake and Deer Creek faults, which show evidence of Quaternary displacement and could represent a nascent dextral system (Spotila and Sieh, 2000). Dextral shear in the hangingwall of the NFTS supports the idea that the ECSZ is growing westward and has replaced thrusting.

The cross-cut model is attractive, because it presents an escape from a structural conundrum of intersecting strike-slip and reverse faults that require different stress regimes in the same volume of crust (Anderson, 1905). The model circumvents the mechanical difficulties of active, intersecting faults by invoking polyphase deformation, which predicts that the thrust fault predates the strike-slip system. Unfortunately, fault activity data have failed to validate this model by proving that the NFTS has become inactive. Demonstrating that any fault is inactive, rather than just slowly deforming with long intervals between seismic activity, is difficult along range fronts in which sedimentation and erosion rates are rapid. Geologic mapping has also yet to delineate a clear cross-cutting relationship at the intersection of the NFTS and Helendale fault (Miller, 1987; Sadler, 1982; H. Brown, Omya (California) personal communication, 1999). The cross-cut model is still testable, however, in that

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**Fig. 4.** Aerial photograph of the western segment of the NFTS (location shown in Fig. 3). Original scale of photograph is approximately 1:30,000, but shown here as ~ 1:65,000. Box denotes location of Fig. 5 and the Marble Canyon paleoseismic site.
it can be disproven or modified if evidence is found for recent activity along segments the NFTS. To evaluate this, and thus learn more about fault interaction and regional seismic hazards, we thus tested the cross-cut hypothesis using paleoseismic and neotectonic techniques. We first used paleoseismology to test whether the NFTS has been recently active. We then used geomorphic observations to evaluate the longer-term activity along each segment of the NFTS, to see what effect the intersecting ECSZ may have had and to develop a kinematic model of this deformation system.

3. Paleoseismic observations

We searched for sites along the thrust system with young tectonic landforms to maximize the probability of identifying recent rupture. This search was limited to the fault segment west of the Helendale fault, to limit possible reactivation due to local convergence or slip transfer within the ECSZ and because reconnaissance revealed numerous sites with apparently young tectonic geomorphology (Spotila and Anderson, 2000). Well-defined thrust fault scarps are common there, but most are inappropriate for assessing recent earthquake activity. High scarps that record cumulative displacement of old alluvium are difficult to date and are not ideal for paleoseismology (Anderson et al., 2003). We focused on small scarps in the alluvium with the least degree of soil development, to capture the most recent deformation.

About 3 km west of the Helendale fault at Marble Canyon, the thrust system consists of several discontinuous, overlapping scarps and folds in Pleistocene alluvium (Fig. 4). The sharpest scarp is several kilometers long, ~5–8 m high, and set within late Pleistocene alluvium of mixed granitic and carbonate composition between older structures to the north and south. It is locally broken by stretches of alluvium with less soil development and appears to have been eroded and replaced by younger deposition (Fig. 5). At one location, a subtle, 1.2-m-high apparent scarp in the younger alluvial (Qa2) surface occurs along strike of the larger, older scarp (Figs. 6 and 7). This feature trends obliquely to the main scarp, allowing it to be interpreted as either an erosional feature along the grain of alluvial transport or an actual scarplet. We excavated this feature, on the chance that it was indeed a degraded fault scarp.

A 20-m-long, 3-m-deep bulldozer excavation across this small alluvial ridge revealed the youngest known displacement along the NFTS (Fig. 8). A coherent stratigraphy of coarse, poorly indurated, ~0.5-m-thick channel gravels is clearly offset by 1.7 m of dip-slip along a N85°W, 23° south-dipping plane. Two thin, poorly sorted, matrix-dominated paleosols are more cemented and appear white due to pedogenic carbonate. All horizons thicken downslope, but the minimal thickness variation across the fault suggests the fault experienced a minimal (if any) strike-slip component. The precise slip vector could not be measured, given the two-dimensional exposure and lack of slickensides on the fault plane. We can thus...
not discount the possibility of minor oblique displacement. Note that the apparent vertical separation of \( B_{kb2} \) is slightly ( \( \sim 25\% \) ) greater than \( B_{kb} \) along the fault. Although this hints at two faulting events, the lack of a colluvial wedge or evidence of a buried ground surface between these paleosols argues this is unlikely. The difference in vertical separation is thus apparent, due most likely to thickness variations in the layers and the fact that the trench, displacement direction, and depositional trend are not mutually parallel. An absence of any cumulative deformation features, such as rotated clasts or multiple shear planes, also argues that this fault plane and offset were produced by a single rupture event.

The fault can be clearly traced to within 1 m of the surface. In the upper portion of the trench, gravel layers are less compacted, less cemented, and sandier, and thus disaggregate easily. The fault is lost where a sandy gravel (G1) is juxtaposed against itself. The uppermost layer is a weak \( B_w \) horizon and does not appear to be offset, although it has probably experienced recent pedogenic reworking. Post-faulting erosion and colluvial deposition has also taken place, based on the absence of the highest
paleosol ($B_{wk}$) and the thicker $B_w$ horizon in the footwall. Whether the missing $B_{wk}$ horizon has been incorporated into the colluvium or was eroded by a channel that ran along the footwall ground surface is not clear. If the footwall surface has been eroded, the vertical separation across this fault scarp is actually greater than the vertical fault offset. In this case, erosional degradation of the scarp partly enhanced its geomorphic expression.

Given the lack of a post-faulting depositional horizon, no minimum age can be established. The maximum age of the event, however, indicates younger displacement than previously suggested for the NFTS. The active soil ($B_w + A$) has minimal redness (10YR5/3) and pedogenic clay and paleosols are all less than stage II calcic (K) horizons, despite being developed in alluvium that consists almost exclusively of marble clasts and calcite sand. Based on this soil chronosequence, the total time required to develop all of the observed pedogenic features is $\sim 20 + 10$ ka (M. Eppes, pers. comm., 2002). This age estimate is corroborated by radiocarbon dating. No datable charcoal was recovered from the excavation, but a radiocarbon age was determined for carbon from a bulk sample of a sand lens from the lowest gravel layer (G3) in the hangingwall. The sand sample was sieved to $<180 \mu m$, treated to remove non-detrital and inorganic carbon (carbonate dissolved in hot HCl baths, roothairs and macrofossils manually extracted), and combusted to yield 14 cm$^3$ of CO$_2$ (0.18% carbon by weight). The resulting accelerator mass spectrometer radiocarbon age of 9710 $\pm$ 50 years BP ($1\sigma$) calibrates to 9220 BC (11,160 years BP) (Talma and Vogel, 1993; Stuiver et al., 1998; Beta Analytic Inc., written communication, 2001). Given the lack of field evidence for groundwater fluctuations, soil redeposition (depositional fabric of overlying gravels is intact), or transfer of humic acids, and the similarity to the soil chronosequence, this age should approximate the deposition of the lowest gravel horizon. Subsequent to this, several meters of alluvium were deposited and weakly weathered prior to the rupture event, thereby indicating that this event was likely Holocene in age. This demonstrates that the NFTS, at least in part, is active.

4. Neotectonic observations

Although we did not identify features suitable for paleoseismic studies along the eastern NFTS, some measure of the relative tectonic activity of eastern and western segments is provided by comparison of neotectonic observations from airphoto mapping and field inspection. The distribution of apparent scarps and other tectonic geomorphic features along the entire NFTS is illustrated in Fig. 9. The proportion of range front that contains mappable fault scarps is significantly greater west of the Helendale fault. East of the Helendale fault, the NFTS is broken by multiple strands of the ECSZ and is manifest mainly as folds or depositional...
bedrock–alluvium contacts (i.e., fault inferred to be buried). Less than 25% of the eastern range front contains apparent scarps, and these are less sharply defined than scarps present along the western segment (Spotila and Anderson, 2000). Slopes of alluvial surfaces along the range front are also less steep along the eastern segment and show abrupt changes at the intersections of major strike-slip faults (Fig. 10). This suggests a lower degree of activity for the eastern segment and demonstrates the effect of intersecting faults on structural tilt and/or depositional patterns.

This west-to-east change in tectonic expression corresponds with a decrease in range-front bedrock relief and total displacement along the NFTS, which reach a maximum near Marble Canyon and taper to zero at the eastern edge of the San Bernardino Mountains (Spotila and Sieh, 2000). A slower rate

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**Fig. 8.** (A) Log of the western wall of a N05°E-trending excavation across the NFTS at location indicated in Fig. 5. East wall of trench displayed comparable stratigraphy and faulting and was not logged. Grid represents 1-m cells without exaggeration. Field classification of soil horizons is indicated in abbreviated form (based on M. Eppes, personal communication, 2001). Layers can be clearly correlated across the thrust fault, including two prominent paleosols (Bkb horizons) that are thinner and more cemented. Sand lenses and clasts shown as gray polygons were drawn precisely, while patterns indicate the general depositional and pedogenic fabric of each layer. Gray-ruled pattern indicates a small area that could not be logged because of a bench dug into the side of the trench wall. Location of bulk carbon sample dated as 9220 BC shown as C1. (B) Photo of the offset Bkb2 paleosol along the thrust fault, from area shown in panel (A). Photo was taken after the log was completed, so minor details may differ.
of activity, shorter duration of activity, or greater period since activity along the eastern NFTS segment could explain this. However, the local geomorphic expression of NFTS is also influenced by variable erodibility, as tectonic landforms are better preserved where indurated petrocalcic soil horizons have developed in alluvium sourced from carbonate bedrock (Eppes et al., 2002). Yet, sharp changes in scarp frequency and total displacement occur at the intersection of the Helendale fault, rather than where

![Fig. 9. Neotectonic map of the NFTS. The NFTS is broken into western and eastern segments at the intersection of the Helendale fault. Tectonic features are illustrated by line weight and shading as fault scarps in alluvium, fold axes in alluvium, or faults manifest in bedrock as lineaments or inferred along the bedrock–alluvium interface. Mapping was based on 1:30,000 airphotos and field observations. Dashed lines indicate boundaries between alluvium dominated by limestone and marble clasts in the middle and alluvium with predominantly gneiss or granite clasts to west and east.](image)

![Fig. 10. Plot of alluvial fan slope from west to east along the NFTS (AA'; shown in Fig. 9). Slopes were measured from fan apexes at a distance of 1 km (near slope) and 2 km (distal slope) from the range front, using 1:24,000 scale topographic maps. The steeper gradients west of the Helendale fault probably reflect higher rates of deformation as well as a more abundant and coarse supply of alluvium (due to greater mountain front relief) and more resistant alluvium due to presence of carbonate parent bedrock. The minima that occur at the intersecting strike-slip faults may result from their influence on deformation or their control on sedimentation patterns.](image)

Table 1

<table>
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<tr>
<th>Site</th>
<th>Scarp height (m)</th>
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<th>Redness (Torrent)</th>
<th>Redness (Harden)</th>
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*a Lithology of parent alluvium listed in order of occurrence; parentheses indicate only minor occurrence.
alluvium changes from carbonate to granitic parent material (Fig. 9). This suggests that the intersection of the ECSZ affects the tectonic activity of the NFTS.

To further evaluate variations in tectonic activity, we measured scarp heights and compared them with characteristics reflecting scarp age along the length of the fault.

Fig. 11. (A) Comparison of fault scarp height and clay content at 30 cm depth in Bt horizons developed on hangingwall surface. Clay content of the <2-mm sized fraction as measured with standard settling techniques is plotted as the x-axis, as would time (for which it should proxy), with scarp height being the dependent variable (assuming uplift rates vary along the fault). Scarp heights were measured in the field using stadia rod and level. Triangles represent scarps from the western NFTS segment and squares represent sites from the eastern segment. Only four scarps were examined on the east, because they are so rare. A rough increase in scarp height with clay content is shown by the regression line, but it is statistically not significant. (B) Comparison of scarp height and redness indices from average wet and dry soil color (Harden index = +10 for each step greater in hue and chroma above the unweathered parent alluvium; Torrent index = hue weight × chroma/value, where hue weights are 5YR = 5, 7.5YR = 2.5, and 10YR = 0; Birkeland, 1999). Both exhibit better correlations than clay content, but eastern scarps are not significantly “older” or slower in uplift rate. (C) Clay content and Harden redness index versus time in other southern California soils, used to calibrate an age proxy. Clay content is shown versus known terrace age from Cajon Pass (McFadden and Weldon, 1987). The correlation with time is excellent, but predicts considerably younger ages for soils on NFTS scarps than expected. The plot of Harden redness versus age is based on soils from the San Joaquin River (Harden, 1982), Cajon Pass (McFadden and Weldon, 1987), and the Antelope Valley (Ponti, 1985). These sites vary considerably in present and past environmental conditions, yet the redness-age correlation is fairly uniform. It thus provides a calibration for redness as a proxy of age that is less sensitive to local climate. Similar results were found for the Torrent redness index using data from Keller et al. (1982) and McFadden and Weldon (1987).
of the range front. In the absence of more quantitative geochronology, we used soil development, represented by clay content and rubification (redness), as a relative proxy for age. Observations were made of Bt horizons (~ 30 cm depth) in soil pits within granitic alluvium at consistent positions along the tops of uplifted hangingwall surfaces. These observations were reconnaissance in nature and do not compose formal chronosequences. They are also representative of relative time only if each hangingwall surface has been preserved from erosion, has experienced the same climate and vegetation cover, and consists of parent alluvium of comparable lithology and grain size. We acknowledge that these restrictions are not always met by the sites investigated, but consider the degree of soil development to be at least a qualitative indication of scarp age.

Redness and clay content increase very irregularly with scarp height and do not define clear differences among eastern and western fault segments (Table 1, Fig. 11A,B). If the eastern segment is less active, its scarps should display greater pedogenic clay content and redness than those of equal height along the western segment. Such a distinction is not apparent from these data. Although clay content and redness may be loose proxies for duration of soil development, they may be too imprecise due to local variations in boundary conditions to resolve differences in fault activity.

Comparisons of these soil characteristics with other regional data provides additional insight on the age of these scarps. Soils developed on alluvial terraces of granitic parent rock in Cajon Pass have higher clay content at a similar depth in Bt horizons (McFadden and Weldon, 1987). The resulting correlation between clay content and age predicts that a soil with 26.5% clay, the highest clay content we observed in our soil pits (site 13, Table 1), would correspond to an age of only 137 ka (Fig. 11C). Although soil development should be faster in Cajon Pass due to higher annual precipitation (~ 50–70 vs. 20–30 cm/year along the NFTS), this comparison implies the fault scarps may be younger than previously suggested. Redness values for Bt horizons from a variety of locations in California also show a correlation with soil age (Harden, 1982; McFadden and Weldon, 1987; Ponti, 1985) (Fig. 11C). Using this relationship, the predicted age of the scarp at site 13 is 0.51 Ma, considerably older than predicted from clay content. Given that the increase in soil redness with time should be fairly uniform for the limited range in precipitation and consistent temperatures found across these California sites, this is probably a more reliable estimate of scarp age (Birkeland, 1999). Using this redness–age relationship for all of our sites, the corresponding scarp uplift rates are 0.19 mm/year and 0.08 mm/year for locations west and east of the Helendale fault, respectively. This comparison is consistent with the hypothesis that the NFTS east of the Helendale fault has a lower degree of relative tectonic activity.

Fig. 12. Simple motion diagram of possible fault interactions in the San Bernardino Mountains (SBM) and Mojave Desert (MD). (A) Vector solution for horizontal shortening rate across the western NFTS segment (NFTS-w), assuming the eastern NFTS segment (NFTS-e) currently experiences an arbitrary shortening of 0.1 mm/year (holding plate A fixed). A dextral rate of 1.0 mm/year is assumed for the northern Helendale fault (HF-n). The resultant vector (velocity of plate A with respect to plate C; \( \Delta V_{AC} \)) implies the western NFTS would need nearly 1 mm/year of oblique–sinistral slip to balance this shortening across the eastern NFTS. (B) Vector solution using the maximum observed shortening rate on the western NFTS of 0.16 mm/year and the assumed rate of 1.0 mm/year on the northern Helendale fault. In this case, the southern Helendale fault (HF-s) is considered inactive. The resultant vector requires >1 mm/year dextral motion on the southern Helendale fault, that cannot be confirmed by existing data. The direction of this motion should be 8° clockwise to that on the northern Helendale fault, which is consistent with the 8° more northerly orientation of the Pipes Canyon fault (Fig. 3). (D) Schematic of proposed eastward migration of the ECSZ. Upper diagram shows deformation pattern today, with an inferred separation (gray line along the trend of the southern San Andreas fault) between domains of thrusting associated with the restraining bend at San Gorgonio Pass (SGP) and dextral shear of the ECSZ (Du and Aydin, 1996). Diagrams below illustrate how the Mojave block moves laterally with respect to the restraining bend, the rate of which depends on what degree the bend is fixed with respect to the opposite side of the fault. Strike-slip faults (A, B, C) are translated with the Mojave block and new fault D initiates, while a portion of the thrust fault is translated into the domain of dextral shear and terminates.
5. Discussion

That the western strand of the NFTS is active has practical implications for regional seismic hazard. A rupture with 1.7-m displacement would be on the order of 40 km long (Wells and Coppersmith, 1994), about the length of the western NFTS. If such a rupture extended to the ~ 15-km-deep base of the seismo-
genic crust ( \( \sim 30 \) km down-dip width), a damaging earthquake of moment magnitude \( M_w = 7.2 \) would result (assuming rigidity of \( 3.3 \times 10^{11} \) dyn cm\(^{-2}\)). Due to relative proximity (Fig. 2c), an NFTS rupture could also affect the seismic cycle of the San Andreas fault. Rupture of a similar thrust fault (Susitna Glacier fault) initiated the November 3, 2002 rupture of the Denali fault (\( M = 7.9 \)) (Eberhart-Phillips et al., 2003), suggesting NFTS rupture could precede failure of the San Andreas’ Mojave segment to the northwest. NFTS rupture would also reduce the normal stress on the San Andreas’ San Bernardino segment to the southeast, thereby bringing it closer to failure (e.g., Stein et al., 1992). Whether such effects are likely to happen in the near future is unknown, however, given that the recurrence history of the NFTS is not constrained.

Our observations also have implications for the behavior of intersecting fault systems. Because the western segment of the NFTS is active, the simple cross-cut model is not valid. The ECSZ has not fully replaced thrusting along the northern range front of the San Bernardino Mountains. This illustrates that using mapped patterns of faulting alone is inadequate for characterizing potential fault activity. It would be incorrect to use the intersection of these faults, which is an unstable quadruple junction that appears to violate simple Mohr-Coulomb failure laws for a uniform stress field (Anderson, 1905), as evidence that one fault system had become entirely inactive.

To fully characterize how these fault systems coexist, the degrees of activity along the NFTS to the east of the Helendale fault and the Helendale fault to the south of the NFTS must be known (Fig. 3). Our neotectonic observations suggest that the eastern half of the NFTS is less active than the western segment. It is possible that it is inactive, given the lack of prominent fault scarps. This is not a robust conclusion, however, given the complexities of geomorphic and pedogenic processes (Eppes et al., 2002). It is appealing, however, in that it avoids having to explain co-active intersecting faults and a quadruple junction with different stress regimes in the same volume of crust or oscillating stress regimes throughout the seismic cycle. It is also reinforced by a simple model that illustrates how the NFTS and ECSZ could be coactive if the eastern segment of the NFTS is inactive (Fig. 12). Treating the blocks between these faults as rigid and two-dimensional, we plot known slip rates in velocity space to resolve what slip the eastern NFTS or southern Helendale fault must have. We assume the northern Helendale fault has \( 1 \) mm/year slip rate, based on roughly equal distribution of the total strain of the ECSZ across the dozen main faults (Sauber et al., 1994).

In the first example, we assign an arbitrary horizontal shortening rate of \( 0.1 \) mm/year to the eastern segment of the NFTS, to see what such a minimal rate of activity would imply for the slip rate on the western NFTS (Fig. 12A). The result indicates that the western NFTS would need nearly \( 1 \) mm/year oblique sinistral-normal motion to balance the motion to the east. In the next two cases, we assume a shortening rate of \( 0.16 \) mm/year for the western NFTS and evaluate what adjacent faults must have to balance motions. This shortening rate is based on the observed fault dip, offset, and the minimum duration of our paleoseismic record (\( \sim 11 \) ka). It could be less, if a substantial period of time passed prior to \( 11 \) ka without rupture. It could be higher, however, if large displacements occurred prior to \( 11 \) ka (or on other fault strands) and were not represented in this paleoseismic record. Although it is inappropriate to calculate displacement rates from offsets without closed time intervals, we adopt this rate for the purpose of our model. Using this shortening rate, a resultant slip vector of \( 1.07 \) mm/year (S\(^{35}\)E) translates to either oblique dextral/reverse motion on the eastern NFTS or dextral motion on the southern Helendale fault (Fig. 12B,C).

Based on our neotectonic observations, it seems improbable that the eastern NFTS could have a slip rate an order of magnitude greater than the western segment. It is more likely that the eastern segment is inactive and that strain from the northern Helendale fault transfers south onto the southern Helendale fault, albeit without a through-going, mappable connection. This would be consistent with the pattern of recent seismicity, that shows a prominence of northwest-trending, dextral fault planes in the eastern San Bernardino Mountains (Fig. 3). The present activity on the southern Helendale fault, however, is not known. It traverses mainly eroded bedrock, so that geomorphic indications of recent activity in young deposits are not clear. Displacement could transfer to
the Pipes Canyon fault, which has a prominent 1.5-km dextral offset of bedrock-incised Pipes Canyon. The Pipes Canyon fault also trends 8° clockwise (N34°W) to the northern Helendale fault, which is the identical rotation predicted by the slip vector model (Fig. 12C). This could be tested by future geologic study. If correct, the model implies future earthquakes produced by the NFTS may be limited in size, given that it is only partly active. However, complex scenarios of rupture involving compound or induced earthquakes between the thrust and strike-slip faults may be possible.

This model is similar to previous interpretations of regional tectonic evolution. Clockwise rotation of dextral faults from north to south in the ECSZ, such as the 20° difference in trend of the ruptures of the 1992 Landers earthquake, has been explained by Unruh et al. (1994) as a result of convergent strain in the San Bernardino Mountains. Our model echoes this proposition, but moves the domain of convergent strain and rotating faults further west. We predict that the triple junction between the NFTS and ECSZ is now at the junction of the NFTS and Helendale fault. Previously it would have been further east, and its westward migration may have been linked with termination of the eastern thrust segment and sequential overprinting by new strike-slip faults. This is consistent with Dokka and Travis (1990b) proposition that deformation within the ECSZ has migrated westward since the middle Pleistocene. The more northerly orientation of strike-slip faults that lie south of the NFTS but east of our proposed modern triple junction, such as the southern Johnson Valley fault (Fig. 3), may owe their orientation to initial formation when the eastern thrust segment was still active. A test of this is whether the southern ruptures of the Landers earthquake involved a component of extension, as they should if their orientations formed more northerly than what is now favored by the regional pattern of strain. This is contrary to the idea that counterclockwise vertical axis rotation causes faults of the ECSZ to rotate out of the north–northwest trend that may be favorable for failure in the regional stress field (Nur et al., 1993).

This model represents a transitional state of polyphase deformation. The local overprinting of dextral shear on the eastern thrust system is analogous to examples of polyphase deformation in microstructural fabrics from the rock record (e.g., Kurz et al., 2000). A potential cause of our proposed westward migration of the ECSZ is southwestwards translation of the Mojave block and ECSZ along the San Andreas fault, with respect to the local geometry of the San Andreas fault. As the Mojave block is advected along the San Andreas fault, it continuously passes through a region that experiences local convergence due to the restraining bend at San Gorgonio Pass (i.e., north–northwest of the bend) and into a domain that experiences dextral shear (i.e., east of the northward projection of the bend at the present-day location of the Helendale fault) (Du and Aydin, 1996) (Fig. 12D). The window of dextral shear propagates west with respect to the Mojave block, but is fixed with respect to San Gorgonio Pass. The predictions and feasibility of this model could be tested with additional geologic data and numerical models of deformation associated with the San Gorgonio Pass restraining bend.

6. Conclusion

The intersection of the Transverse Ranges and Eastern California shear zone provides an interesting structural setting for investigating fault interaction. Our paleoseismic observations indicate that the North Frontal thrust system has experienced surface rupture in the Holocene and should be considered an active fault and a potential source of future large earthquakes. This further indicates thrust system has been coactive with individual strands of the Eastern California shear zone that intersect it, such as the Helendale and Old Woman Springs faults. This suggests that a simple cross-cut model, in which one fault system postdates the other, is not valid. Based on neotectonic observations, the segment of the thrust system east of the Helendale is interpreted to be considerably less active than the western segment. This fits with a simple rigid block velocity model, in which estimates of slip rate on the Helendale fault and western thrust segment can be reconciled as a quasi-stable triple junction that would be completed by the Pipes Canyon fault to the southeast. We further speculate that this system is transient, as the Eastern California shear zone propagates to the west. If correct, this model predicts that this system of inter-
secting faults is active in a complex, polyphase fashion, which was not apparent from mapped fault patterns alone. Detailed geologic investigations of such complex fault systems are thus important for understanding the kinematics of active deformation and fault evolution.

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