The paleoseismic and neotectonic history of the North Frontal thrust system of the San Bernardino Mountains, southern California: Investigating complex fault interactions and possible implications for the San Andreas fault, while characterizing the seismic hazard of a major structure in the growing Inland Empire

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Introductory Statement

This report follows closely the Annual Project Summary that was submitted on November 1, 2000. The first year of this award began on March 1, 2000. Since submission of the Annual Report, little additional progress has been made. We are still waiting for results on cosmogenic exposure ages, and are awaiting our second field excursion in a few weeks during which we will begin our fault excavations.

Progress statement

Progress on this project has proceeded very well so far. Our initial field work, lab work, and airphoto mapping, summarized below, have produced interesting results. Our April field excursion refined our plan for fault excavations, but we have not yet undertaken a second field excursion. The summer of 2000 was avoided due to hot working conditions, while the fall of 2000 was not a feasible time for field work given the teaching responsibilities of the Principal Investigator. We have scheduled our second field excursion for January 20 through February 10, 2001. Airline tickets have already been purchased and other arrangements have been made. Graduate student, Kevin Anderson, will accompany the PI on this trip.

We have set up valuable collaborations with two mining companies along the rangefront. We will excavate the fault at two locations, both of which fall on mining company property. The companies, Specialty Minerals Inc. and the Mitsubishi Cement Corporation, have granted us permission to conduct our excavations. They are also providing us with heavy equipment to make the excavations. This will save a considerable amount of expense. We are looking forward to getting back to the field in a few weeks and working with these companies.

Investigations undertaken

A. March and April, 2000; airphoto mapping Airphotos were purchased and mapped, with the goal of delineating the most recently-active structures for closer investigation while in the field.

B. April , 2000; field investigations Two weeks of field work were conducted by Spotila. This involved examination of possible structures that had been identified on airphotos and detailed investigation of recently-active fault structures. These investigations involved measurement of fault scarp height and profile and examination of soil horizons developed on faulted alluvium. Soil samples for later analysis were taken, as were surficial fragments of 4 large boulders on faulted fanglomerate surfaces for cosmogenic dating. Scarps were sampled along the entire rangefront.

C. June - November, 2000; airphoto mapping and soil analysis Continued airphoto mapping was conducted by a new M.S. graduate student, Kevin Anderson. This mapping will lead to final preparation of a neotectonic map, and also served to acquaint Anderson with the field area. Soil samples collected in April were also analyzed for color and grainsize distribution (i.e. clay content).

D. August, 2000; cosmogenic sample preparation Rock samples taken from large boulders on faulted fanglomerates were cut and prepared for cosmogenic dating. Samples were sent to *PRIMELAB* (at Purdue University) for chemical treatment and measurement of ^{26}Al and ^{10}Be on the Accelerator Mass Spectrometer.

E. September - November, 2000; analysis and presentation Spotila and Anderson wrote an abstract for the Geological Society of America's annual meeting in Reno, analyzed existing data, and prepared a presentation that addresses the main questions of this study.

F. January, 2000; trenching We are planning a second field excursion for early to mid-January.

Results

The goals of the proposed study were to 1) assess the rupture potential of a thrust fault possibly capable of M7+ earthquakes in southern California; 2) assess the recurrence and position within the earthquake cycle of a thrust fault that may mechanically influence the San Andreas fault; 3) explore the relative behaviors of three thrust segments that are mutually separated by intersecting dextral faults of the eastern California shear zone, with the purpose of learning how intersecting faults analogous to those in the Los Angeles Basin function.

The first and second goals will be best answered by excavating the fault at sites that are the best candidates for recent displacement and which exhibit stratigraphy that can constrain the age of faulting. Thus far, field observations and airphoto analysis have identified two locations for trenching on the western segment (Figure 1). We plan to excavate at these sites in January, 2001 (still within the first year of this award). The third goal can be addressed by both paleoseismic excavations and neotectonic observations at all three segments. We plan to excavate candidate fault scarps along each of the eastern and central segments in the second year of this award.

Neotectonic observations may show how the thrust fault segments have behaved (i.e. quantify deformation) in recent geologic time (late Pleistocene to Holocene) and thus bear on the third main question. We have addressed this in 4 ways. **First,** our airphoto mapping, which is still in progress, has shown that young-looking fault features are much more common along the westernmost segment (west of the Helendale fault). Figure 1 shows a preliminary summary of mapping from 1:30,000 scale airphotos. Note that young fault scarps are common to the west of the Helendale fault, but rare along the central and eastern segment. Clear, sharp fault features in alluvium make up less than 25% of the length of the eastern and central thrust segments, whereas most of the faultzone is represented by bedrock features or dull bedrock-alluvium contacts (blue lines, Figure 1). Scarps are so rare east of the Helendale that only a few sites were available for measurement of scarp height in the field (Figure 1). The Helendale fault may be an important segment boundary, separating a more active western segment from less active ones to the east.

An alternative explanation is that the style of faulting changes at the Helendale fault intersection, perhaps from simple reverse faulting on the west to folding in the foreland basin on the east. Folds do occur north of the rangefront along the central segment, suggesting a possible northward migration of deformation (Figure 1). To evaluate this, we plotted the variation in slope of alluvial fan apex axes along the rangefront. Figure 2 shows how slopes of fan apexes that are 1 km north of the range and 2 km north of the range (near and distal, respectively) vary. Note that the eastern and central segments are not more steeply tilted than the western segment, suggesting that a greater proportion of folding is not occurring east of the Helendale fault. This is consistent with the idea that deformation rates are lower there. Fan gradients also change at the intersections of the Helendale and Old Woman Springs fault. This is consistent with the idea that these intersecting strike-slip faults are affecting the deformation along the thrust fault. We plan on continuing this **second** line of investigations, by completing more detailed measurements of fan slope along the rangefront, normalizing for fan age and lithology. We also hope to look at the grainsize distribution of alluvium along the rangefront, to see if there are variations that cannot be explained by catchment size or bedrock type and therefore may indicate variations in erosion rate.

We have used soil development along faulted surfaces and scarp morphometry as proxies for age to determine the relative deformation rates across the 3 thrust segments. For this **third** approach, we measured scarp height and profile and sampled hanging-wall and footwall soils at 16 locations (Figure 1, Table 1). Soils were sampled from a uniform depth (20-30 cm) in Bt-horizons developed on alluvial surfaces, and have subsequently been analyzed for rubification (redness) and grainsize distribution. Both redness and clay content should increase with soil age, thus giving a semi-quantitative estimate of relative age among scarps (Harden, 1982; Birkeland, 1991). To test this simply, Figure 3 shows plots of clay content and redness vs. scarp height. Redness is given as two measures; the Torrent Index (= hue weight x chroma / value, where hue weight; 5YR = 5, 7.5YR =

2.5, and 10YR = 0) and the Harden Index (average of wet and moist colors, +10 for each step greater in hue and chroma above the parent material [unweathered alluvium, 10YR8/3 in this case]). If all scarps were forming at the same uplift rate, redness and clay content should increase evenly with scarp height. Though they do increase, the correlation is not good. What may be important, however, is that the eastern and central scarp sites do not systematically occur below the regression lines. That is, if the scarps on the central and eastern segments were significantly older for their size than those on the west (i.e. because of a slower uplift rate), we would expect them to have proportionately more clay and redness. This is not the case, suggesting that either the different segments have the same uplift rate or that the increase in clay content and redness with age is not uniform enough to distill a meaningful relationship to scarp age or uplift rate.

To get a more meaningful comparison, the clay content and redness of these soils were compared to other California locations. First, we compared clay content (normalized to the <2 mm fraction) to values from 30 cm deep Bt horizons on 5.9 Ka to 500 Ka soils of granitic parent rock on Cajon Pass terraces (McFadden and Weldon, 1987). In Cajon Pass, clay contents of 24% occur in soils that are only 55 Ka. This is surprising, given that this is the highest clay content we observe in faulted alluvium. When plotted vs. log10 of age (Figure 4a), there is a clear correlation between age and clay content from the Cajon Pass soils. Using this relationship, we estimated the age of our soils and converted to uplift rate by dividing into scarp height (using only granitic soils). The average uplift rate based on this comparison is ~0.9 mm/yr for the rangefront scarps. This is quite surprising, given that the thrust should be decelerating with time and given that the longterm rate is slower. Ages based on comparison with Cajon Pass soils are thus likely underestimated, perhaps because Cajon Pass receives greater precipitation or has other different factors. However, it does imply that scarps along the thrust fault may not be as old as previously considered.

We also attempted to use redness to compare scarp age on the different thrust segments. Using Harden Index data from alluvium along the Merced River in northern California, we derived a linear relationship with age (Figure 4b; Harden, 1982). Using this function, we estimated ages of our soils based on their average Harden Index and then computed uplift rates by dividing into scarp height. Based on these estimates, the average uplift rate for scarps developed in granitic alluvium on the western segment is 0.25 mm/yr, whereas the average for scarps developed on the eastern and central segments is only 0.07 mm/yr. This again suggests that the western segment is more active. The Torrent Index reveals similar results. Based on the Cajon Pass soils of McFadden and Weldon (1987), 55 Ka soils have Torrent Indeces of 5 or greater. We thus took all of our granitic soils that have average Torrent Indeces <5, assumed these were 55 Ka or younger, and computed minimum uplift rate (by dividing by 55 Ka). Based on this, average uplift rate on western scarps was found to be 0.23 mm/yr. On the east, only one scarp fit this criteria, and since it was 3.6 m high, the rate determined was 0.07 mm/yr. Also on the east is the one scarp with a Torrent Index as high as the 500 Ka age at Cajon Pass (T = 9.3). Assuming this scarp is 500 Ka gives an uplift rate of 0.11 mm/yr. These results, based on two different data sets and indeces for redness, produce similar results. The results suggest that uplift rates are indeed greater on the west than on the east or central segments. They also imply that rates are as high as about half of what the long term rate should be (0.8-0.53 mm/yr [Spotila and Sieh, 2000]). These results are also consistent with soils from Indio, California (Keller et al., 1982). Although they only provide us with loose estimators of relative age among segments, they may be indicating an important difference from west to east.

Scarp morphometry also implies that the western thrust segment has been more recently active. The maximum slope of scarp fronts, as measured in the field using an inclinometer,correlates very roughly with scarp height and lithology of faulted alluvium. Higher scarps should, in general, have steeper maximum slopes (Figure 5a). This is consistent with ideas about scarp erosion rates correlating with the total relief across scarps. Carbonate-rich alluvium also retains higher scarp slopes, because carbonate dissolution and pedogenic formation of hard caliche probably armours scarp fronts (Figure 5b). When maximum scarp slopes developed on granitic alluvium are normalized for height, however, it is clear that the western scarps are steeper than the average normalized slope, whereas the eastern and central scarps are more gentle than the average scarp slopes (Figure 5c). This is consistent with the idea that western scarps are younger, because they have had less time to degrade to lower slopes.

Although these results imply that the western segment may have a faster slip rate and that rates may be faster than implied previously (i.e. close to 0.25 mm/yr), we must really wait for the quantification of scarp age from cosmogenic dating. In this fourth approach, we have collected 4 samples for dating (^{10}Be and ^{26}Al) on >2 m diameter boulders on faulted alluvium (C's, Figure 1). These are being processed by *PRIMELAB* and the results should be back within a few months. Our hope is that these ages will determine the absolute, late Pleistocene slip rates on each thrust segment.

Reports published

1) Spotila, J.A. and Anderson, K.A., 2000. Assessing the behavior and seismic hazard of complex thrust and strike-slip faulting along the northern front of the San Bernardino Mountains, southern California (abstract), *Geol.Soc. Amer.*, Abstracts with Programs, Annual Meeting, Reno, NV.

2) Spotila, J.A. and Sieh, K., 2000. Architecture of transpressional thrust faulting in the San Bernardino Mountains, southern California, from deformation of a deeply weathered surface, *Tectonics*, 19, 589-615. (note that this work was funded by the Southern California Earthquake Center and was completed prior to the start of the current NEHRP award, but it is included because it is directly relevant to the study region and main problems)

Data availability

As of yet, no seismic, geodetic, or other processed data are available. Age data may become available by early 2001.

Figure 1: Neotectonic map of the North Frontal thrust system, based on airphoto mapping and field investigations.

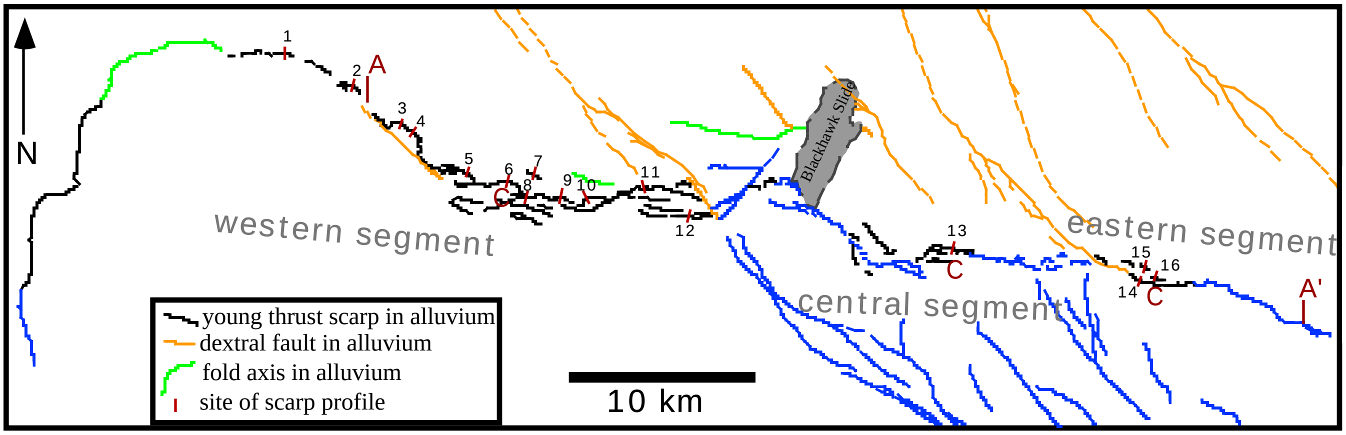


Table 1: Scarp data.

Site	Scarp (m)	Lith.	% Clay	Red (Torr.)	Red .(Harden)
1.	13.3	gr	9.68	4.43	40
2.	33.6	gr	9.56	4.92	46.7
3.	13.0	gr	8.93	0.83	20
4.	45.6	gr	22.47	5.50	46.7
5.	11.6	gr/gn/lm	24.61	4.35	36.7
6.	12.8	gr	9.75	0	6.7
7.	6.6	gr	7.18	0	13.3
8.	4.5	gr	-	-	-
9.	39.6	lm	-	-	-
10.	9.2	lm	3.23	-	6.7
11.	51.2	lm	-	-	-
12.	18.2	gr/lm	2.64	0.83	20
13.	54.5	gn/gr	17.48	9.23	60
14.	46.2	gn	5.17	4.86	43.3
15.	3.6	gr/gn	9.37	4.35	36.7
16.	14.9	gn/gr	4.35	5.31	46.7

Figure 2: Alluvial fan slope vs. distance

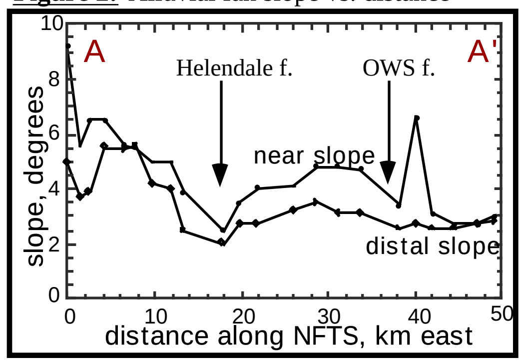
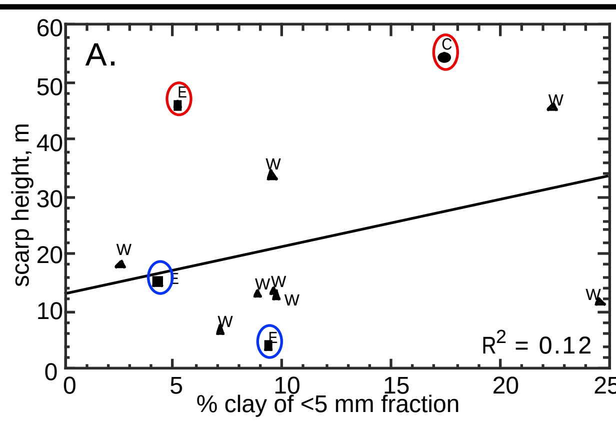
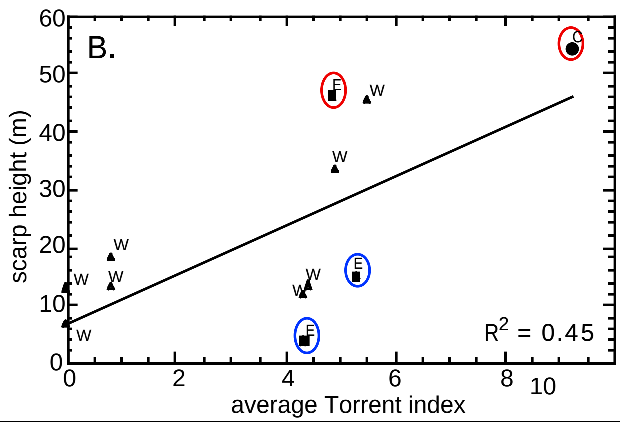


Figure 3: Clay and redness of Bt1 horizons vs. height of fault scarp. A) Clay content increases roughly with scarp height, but eastern and central scarps are not systematically more clay rich (i.e. older) for their height relative to western ones. B) Scarp height vs. the average Torrent Index redness for soils, and C) scarp height vs. average Harden Index of redness also show that redness roughly increases with scarp height, but central and eastern scarps are not consistently more red (i.e. older) than western ones.





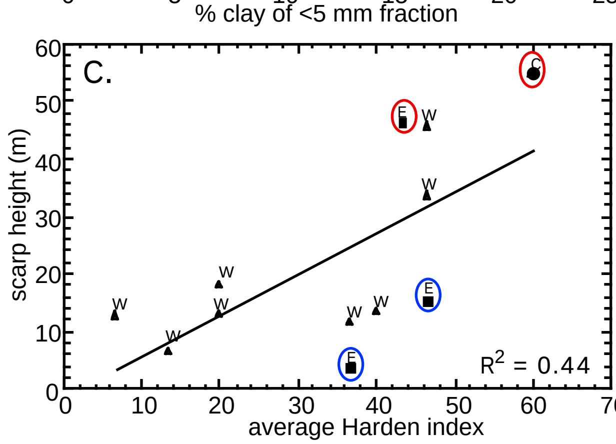


Figure 4: A) % clay of <2 mm fraction on soils from Cajon Pass vs. soil age (McFadden and Weldon, 1987). B) average Harden Index for soils from the Merced River vs. age (Harden, 1982). Both represent B horizons that are 20-40 cm deep.

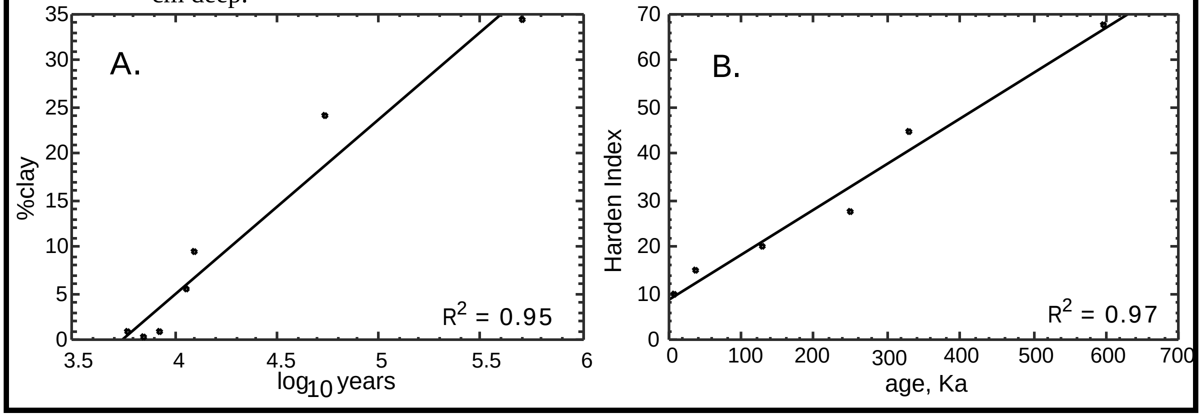


Figure 5a: Maximum scarp slope, measured in the field, vs. scarp height, showing how higher scarps have steeper frontal slopes.

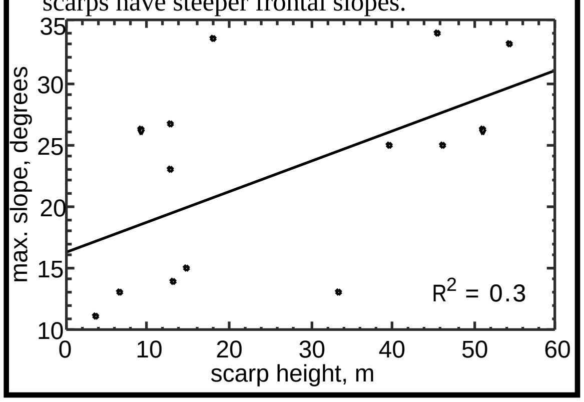
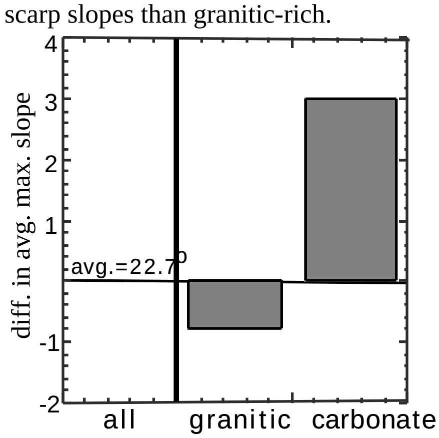


Figure 5b: The difference between average maximum scarp slope on all 16 scarps vs. the average maximum scarp slopes developed on granitic-rich and carbonate-rich alluvium. Carbonate-rich alluvium clearly retains higher scarp slopes than granitic-rich.



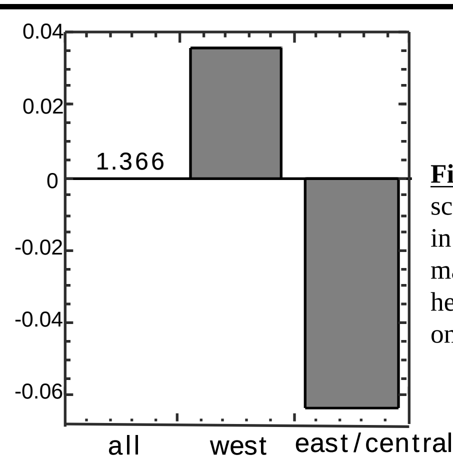


Figure 5c: Difference between normalized maximum scarp slopes (normalized by scarp height) on granitic alluv. in different thrust segments with the average normalized maximum scarp slopes (divided individually by scarp height) for all scarps. Illustrates that slopes are steeper on the west, once differences due to height are eliminated.