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 in the growing Inland Empire

External Grant Award Number: 00HQGR0028

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NEHRP Element(s): II (SC) **Keywords:** Neotectonics, Fault Segmentation, Paleoseismology, Quaternary Fault Behavior

Investigations Undertaken

Investigations of the North Frontal thrust fault along the San Bernardino Mountains in southern California shed new light on regional seismic hazards and the behavior of intersecting fault systems. Using airphotos and field observations in 2000, we mapped the tectonic geomorphology of the 80-km-long thrust system. Results show numerous fault scarps of youthful appearance on the western half of the fault zone. Field surveys of many of these scarps show that they are quite sharp and may be as young as late Pleistocene. Comparison of soil development along faulted alluvium with published soil chronosequences also suggests these scarps may be younger than previously considered. We speculate loosely based on these soil comparisons that rates of uplift along the thrust fault may be as high as 0.25 mm/yr, about half of the long-term rate. This is much higher than previously predicted. Cosmogenic exposure age dating of fault scarps will add an independent measure to this rate estimate (we are still awaiting useful data from PRIMELAB (Purdue University's AMS facility)). These initial results do hint that the thrust system is segmented. The youthful scarps along the western segment are in contrast to the less-active appearance of the eastern and central segments. The intersection of strike-slip faults associated with the Eastern California shear zone may create segment boundaries, that dissect the thrust system into independent segments that fail in smaller events. Before we can reach such a conclusion, however, additional constraints on the slip rates, 3-d structure, and paleoseismic history must be found.

In addition, our field work in January and February of 2001 (J. Spotila and M.S. Student Kevin Anderson) resulted in discovery of a very young rupture in an excavation across the thrust system. Previous neotectonic mapping has pin-pointed several locations ideal for trench excavations. Near the center of the fault zone just west of the Helendale fault (Figure 1), we excavated a small ridge in younger alluvium situated between two 5-m-high scarps in late Pleistocene alluvium. The thrust fault was discovered, showing a simple, clean break of about 1.7 m thrust displacement. Based on estimates of soil development age by M. Eppes (U. New Mexico), the entire stratigraphy of the exposure may represent ~20 Kyr. Given that the fault cuts most of these layers, the rupture event may be considerably younger. Detrital charcoal taken from one of the lowest gravel layers of the hangingwall (buried under 2 meters of alluvium) has been dated by Beta Analytic as 9710±50 BP. This date provides a maximum age for the rupture and indicates Holocene displacement along the thrust fault. Although we cannot place a minimum age on this rupture event, the deposition and soil development of the units overlying the 9.7 Ka gravel probably required the majority of this period to deposit and develop, suggesting the later fault event has been quite recent. Excavations planned for January of 2002 may further constrain the timing of this rupture event, as well as test how far along strike it may have continued.

Results

The purpose of this investigation is to assess the rupture potential and displacement history of a major thrust fault in southern California. If still active, the North Frontal thrust system along the northern flank of the San Bernardino Mountains may be capable of M7+ earthquakes. This thrust is also in close proximity to the San Andreas fault zone, and if it accumulates and releases convergent strain it may mechanically influence the failure cycle of this major strike-slip fault. Both of these structures may represent serious seismic hazards in the Inland Empire. In addition, the structural setting of the North Frontal thrust system provides a good analogy to the complex thrust-strike-slip fault intersections in the Los Angeles Basin. The thrust system is intersected by numerous strands of the southern Eastern California shear zone, which may break the thrust into discrete, independent segments. By comparing the reaches of the thrust system in-between the strike-slip fault intersections, we hope to learn about fault segmentation and become better equipped to predict rupture patterns in the structurally similar Los Angeles metropolitan area.

Our study has taken two approaches thus far. First, we have mapped the entire thrust system using air-photos and field observations, so that characteristics indicative of recent activity can be compared along different fault segments. This addresses the question of whether differences along the trends of the thrust system are associated with segment boundaries represented by the strike-slip faults. It also helps qualitatively constrain just how much recent activity the thrust fault has experienced (e.g. the presence of Holocene scarps). Along a similar vein, we have surveyed fault scarps and characterized soils along each of the major thrust segments. Using soil development as a proxy for age, we are able to compare the relative rates of late Pleistocene activity between each segment boundary. In addition, we have collected material for cosmogenic exposure age dating (^{26}Al, ^{10}Be) along scarps at each section. We have collected four samples on >2 m diameter quartz-rich boulders on faulted fanglomerates (C's, Figure 1). These ages will help constrain the absolute late Pleistocene slip rate along the fault, and may show whether the western segment has a faster slip rate as suggested by tectonic geomorphology and characterization of soils along the rangefront. Altogether, this work will provide a very good characterization of both the late Pleistocene displacement history of the fault zone and the relative activities of segments between the strike-slip fault intersections.

Our neotectonic mapping indicates that young-looking fault features are much more common along the westernmost segment (west of the Helendale fault). Figure 1 shows a summary of our 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 fault zone 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; based in part on mapping by the USGS [J. Matti, B. Powell]). An important contribution to this question has been made by other workers (M. Eppes and L. McFadden [U. NM], F. Pazzaglia [Lehigh U.]) with whom we are collaborating. They have pointed out that folds are clearly visible only where preserved from erosion. This preservation in unconsolidated alluvium is largely dependent on high pedogenic carbonate content, which in turn is dependent on the lithology of drainage basins. As a result, the only areas in which folds may be preserved may be the basins with large marble concentrations. This is true of the drainages just to the east of the Helendale fault. In February, 2001, we had the opportunity to meet with M. Eppes in the field and explore some of these fold features. With luck, future investigations by both our groups will help assess the role of folding in the deformation history of the thrust system.

The second approach to our investigation is to characterize the paleoseismic history of the thrust system. This addresses all of our main questions, including whether the fault is active, what its seismogenic potential is, what step in its loading cycle it presently sits and how this may affect the San Andreas fault, and whether it is broken into independent thrust segments that rupture separately or may fail in single, large events. Ultimately we require paleoseismic investigations along each of the three main fault segments. Thus far we have completed excavations along the western segment (which is also the largest) and found evidence for Holocene displacement. Below we describe our main results.

In our initial investigations we selected two locations for fault excavations in our first year. Locations were selected on the basis of the youngest-looking tectonic geomorphic features that could indicate the most recent rupture. In addition, we chose sites in which young alluvium would cover the rupture zone, thereby providing an onlapping cross-cutting relationship (i.e. provide a minimum age for the rupture event). For example, we did not want to excavate the fault where 5- or 10-m high scarps occur, because this would only show offset stratigraphy that was too old to date using ^{14}C (given the suspected slow rate of activity along the fault).

The two locations that appeared most promising both occur along the western segment of the thrust system (Figure 1). Location "Mits1" is located along the Mitsubishi Cement Corporation property and consists of a very sharp, 5-high scarp in late Pleistocene alluvium that has been locally eroded away by younger deposits (Figure 2a). Across a ~0.1-km-length the fault scarp has been eliminated and younger deposits have been laid down. A very faint, ~1-m-high ridge occurs across this area (Figure 2b) and appears to connect the larger, older scarps. We selected this ridge as a target for our initial excavations and completed this work in February, 2001. Location "SM1" is located along the Specialty Minerals Inc. property. It too represents a location where a sharp, 8-m-high scarp has been incised and younger alluvium has been deposited across the fault (Figure 2c). An active wash has laid several meters of younger alluvium across the fault in-between sections of the scarp, but no small ridge or scarp breaks the younger depositional surfaces (Figure 2d). Although this site is very promising, we did not have time to excavate it in our first year. This is partly because of the thick young alluvium, which requires the excavation to be significantly deeper than at site Mits1. We aim to excavate this site in a field excursion in 2002.

Our excavation at site Mits1 was facilitated by cooperation with the Mitsubishi Cement Corporation, which graciously provided a D-8 bulldozer at no cost. The excavation extended approximately 20-m long and 3-4 m deep and required no shoring or terracing. A thrust fault was clearly exposed, juxtaposing gravel layers and paleosols on either side (Figure 3). We surveyed the area prior to excavation with a total station, and logged and surveyed the excavated exposure at a scale of 1:10. Figure 4 is a preliminary compilation of our trench log.

Two thin, poorly sorted gravel layers with moderate pedogenic cement are clearly offset by the fault. Based on detailed observations of depositional and pedogenic character, the layers can be restored (HW2 to FW2, HW4 to FW4; Figure 4) with a large degree of confidence. Because the depositional strike of these deposits is not identical to the fault strike, downstream thickness variations in the units result in thickness variations on either side of the fault in the two-dimensional section. The visible differences in thickness of the main units in the footwall and hangingwall may thus result entirely from pure-thrust juxtaposition and does not necessarily indicate any strike-slip component of motion. However, given that we did not perform a three-dimensional excavation, we cannot rule out the possibility that a slight strike-slip component is present. The average throw along the fault represented by the different offset units (A to A', B to B'; Figure 4) is 1.66 m ($\pm$0.1 m). Because the fault itself consists of single, simple fracture plane without multiple strands, and because the layers all share about the same offset, we infer that this fault and juxtaposed layers represent one rupture event. This is consistent with the magnitude of displacement, as 1-2 m of throw would be expected from a ~20-40 km long surface rupture connected to a rupture plane at depth that extends to the base of the brittle crust (Wells and Coppersmith, 1994). This could represent failure of most of the western segment of the thrust system. It is also possible that the rupture continued to the east, across the Helendale fault, but we cannot test this until additional paleoseismic work is complete.

Detrital charcoal samples for ^{14}C dating were extracted from numerous locations in the exposure (black dots, Figure 4). These were sent to *Beta Analytic* for AMS dating, but unfortunately none yielded the minimum required carbon yield (at least 0.5 mg). Instead, a bulk sediment sample has been sent to Beta Analytic for bulk organic ^{14}C dating. This sample was taken from location 1 (Figure 4) and consisted of fine carbonate sand and silt in a small channel lens. Very fine detrital charcoal was separated from this sediment and non-detrital organic material was removed (e.g. root hairs, etc.). We are confident that the carbon dated was indeed primary organic carbon deposited with the silt and sand. Because the layer dated was not exposed for significant time, based on the lack of a paleosol directly atop it, it is unlikely that the carbon was incorporated after deposition via eolian inputs or bioturbation. The original depositional fabric of the gravels above is intact, suggesting this sand lens has been preserved since deposition. The resulting age was measured to be 9710±50 yrs before present. The resulting age is consistent with an estimate of the total time required to produce the paleosols and active soil horizons of the exposure; roughly 20 Ka (+10 Ka) based on a soil chronosequence by Martha Eppes (U. New Mexico; personal communication; April, 2001). This age estimate was made before the radiocarbon results were available. These ages are essentially in agreement and indicate the maximum age of this thrust fault rupture. Deformation of these layers had to post date the deposition and weathering of the major units shown, and thus had to have ruptured well after the deposition of the 9.7 Ka detrital charcoal. This indicates Holocene displacement on the thrust.

Stratigraphic relations in the exposure did not offer constraint on the minimum age for the event. The highest layer clearly offset by the fault is FW5, which should correlate with HW5, but no fault could actually be identified where these two layers are juxtaposed (location 2, Figure 4). Note that the hachured area in the trench log near this location represents where we dug a ledge into the side of the exposure to enable access to the higher areas. This ledge and our secondary disturbance of the stratigraphy made it locally impossible to log. However, adequate exposures near location 2 failed to show a fracture trace. Both layers FW5 and HW5 are very loose and consist of a large fraction of sand, such that a fracture may not be preserved even if these layers predated the rupture. In contrast, the layers below are more-well cemented. Because the base of this layer is clearly offset and given the difficulty of preserving fractures in sandy, unconsolidated sediment, we infer that the rupture did in fact propagate through this entire layer. Above this layer in the hanging-wall is a poorly sorted, moderately-cemented gravel layer HW6, which is not found in the footwall. We suspect that post-faulting erosion of the scarp has removed the upper portion of this layer in the hanging-wall and the entire portion of this layer in the footwall. This is supported by the observation that the vertical separation of layers along the fault is less than the height of the scarp (Figure 2b). Probably at the expense of layer HW6, bioturbated, weathered colluvium has built up along the top and base of the scarp, although this layer is considerably thicker along the footwall (Figure 4). This makes up layer HF7, which is continuous and represents the modern soil horizon. It consists of unsorted gravel and loam and displays very minor soil development, extensive bioturbation, and eolian silt. Although the soil development in this layer post-dates the rupture, we found no detrital charcoal within it to date. We chose not to date the bulk organic material in this layer, because the high degree of bioturbation probably led to significant recycling and influx of younger organic material that would result in an inaccurate minimum age for the rupture event. Thus, this exposure only provides control on the maximum age of the rupture.

The results from this excavation are significant for the North Frontal thrust system. Previous workers have suggested that the thrust is inactive or nearly so, on the basis of an apparent decline in late Pleistocene slip rates. The young rupture which we have documented suggests this is probably not the case, and that the thrust system has actually been active in the Holocene. Unfortunately, we do not yet know how long it has been since its last rupture, so we cannot speculate on the status of the fault's elastic strain cycle, which may be important for the San Andreas fault. We will address this question in 2002, by excavating site SM1, where it is likely that onlapping sediments will provide a minimum age for the fault event. We also have not yet determined the extent of this rupture, to investigate the role of segmentation along the thrust system. We may address this with future excavations along other fault segments, although it is unclear whether adequate sites will be found.

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3) 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.

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

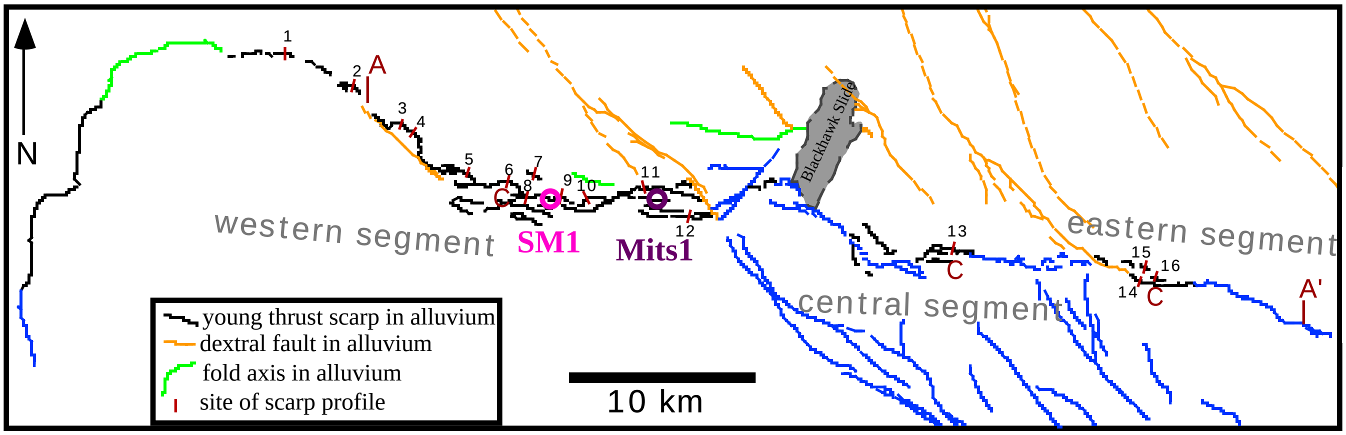

Figure 2a: Profile of main scarp at site Mits1.

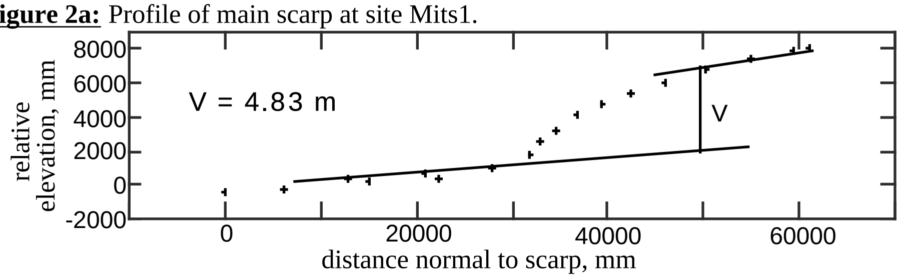

Figure 2b: Small scarp profile (trenched) at site Mits1.

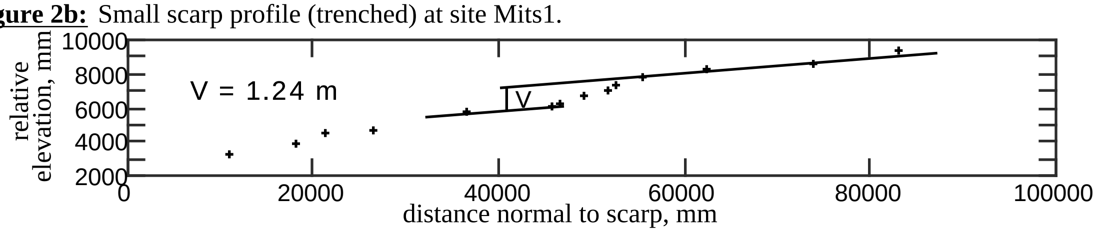

Figure 2c: Profile of main scarp at site SM1.

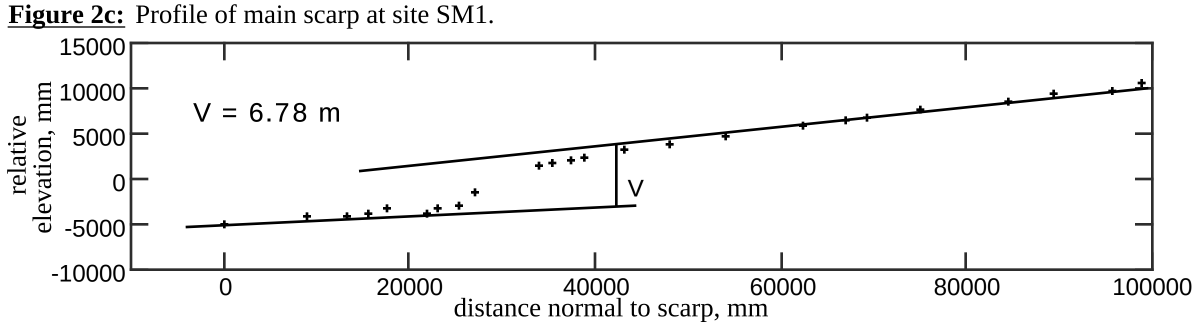

Figure 2d: Profile up young alluvium between scarps at site SM1.

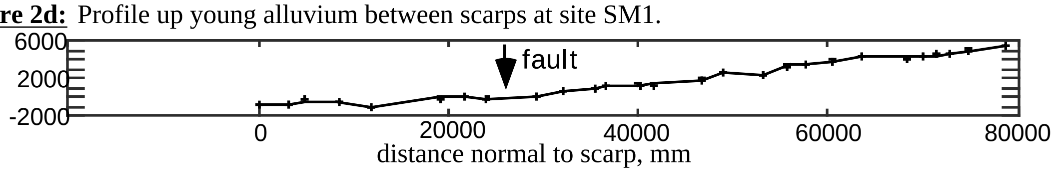

Figure 3: West wall of the Mits1 excavation site, showing the 1.7 m thrust offset of a carbonate paleosol, layer HW2 over FW2. Charcoal dated at 9.7 Ka came from the yellow flagging, just above the orange tape measure.

Figure 4: Trench log of west exposure of the Mits1 site. Scale is indicated by the 1-m grid overlaid on the log. Original trench log was made as a mosaic of grid blocks drawn at 1:10 scale and surveyed in with a total station. Color indicates 3 paleosol layers in the hangingwall (HW2, Hw4, and HW6) and two corresponding layers in the footwall (FW2, FW4). There is no corresponding FW6 (it has been eroded). Inbetween these poorly developed carbonate paleosols are coarse gravel units with original bedding intact. HF7 covers the entire exposure and represents the modern soil. It is weakly developed and has been affected by bioturbation and eolian influx. It is not clear how far upwards the fault cuts, as the region at location 2 consists of disagregated material in which no fault can be observed. Charcoal was dated from location 1.