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THE ROSE CANYON FAULT ZONE IN SAN DIEGO

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ABSTRACT

The Rose Canyon fault bisects the City of San Diego, producing much of the unique beauty of the city with the uplift of Mt. Soledad and subsidence producing the natural harbor of San Diego Bay. Geologic studies demonstrate that the late Quaternary slip rate is in the range of 1-2 mm/yr, which although only a fraction of the plate margin slip budget, has the potential to produce major damage in "America's finest city". Paleoseismic trenching in La Jolla and downtown San Diego indicate that the most recent surface rupture occurred only a few hundred years ago, sometime after about AD1523 but prior to the establishment of the SD mission in 1769. Displacement in this earthquake may have been as much as 3m based on 3-dimensional trenching. Using this displacement and slip rate, the average return period should be on the order of 1500 -3000 years, suggesting that San Diego may be safe for the near future. However, limited observations suggest that the Rose Canyon fault behaves in a clustered mode, where earthquakes are clustered in time, rather than in a quasi-periodic fashion. If correct, and considering that the rupture in the past few hundred years appears to have been the first large earthquake in more than five thousand years, San Diego may have recently entered a renewed period of activity.

INTRODUCTION

The Rose Canyon fault is the primary potential seismic hazard to the City of San Diego due to the faults' proximity: a moderately large earthquake could potentially do significant damage to the City and surroundings, both in terms of shaking and ground rupture. In this paper, I briefly describe the current state of knowledge on the location, slip rate, timing and size of past large events on the fault in the City, and speculate on its behavior and the potential implications for the likelihood of future damaging earthquakes.

In the broad scheme of plate tectonics, the Rose Canyon fault is a bit player, as it accommodates less than 5% of the total plate motion (Figure 1). The fault is part of a coastal system of faults that accommodate 6-7 mm/yr between San Clemente Island and the mainland. From the south, the Agua Blanca fault in northern Baja California feeds slip northward at about 5-6 mm/yr (Rockwell et al., 1993), with this deformation principally accommodated by the Rose Canyon, Coronado Bank, and San Diego Trough faults. Farther offshore, the San Clemente fault appears to extend southward of the Agua Blanca fault (Legg, 1985), and may be part of a zone that extends the length of the Baja peninsula. To the north, the Rose Canyon fault becomes the Newport-Inglewood fault, and this zone of active faulting extends northwestward through the Los Angeles basin to the Transverse Ranges (Figure 1).

Within San Diego, the Rose Canyon fault zone comprises a broad zone of active and inactive strike-slip and normal faults (Figure 2). Mt. Soledad is interpreted as a pressure ridge where the fault makes a left or transpressive bend, producing local uplift. Kern and Rockwell (1992) show that this deformation has continued into the late Quaternary with uplift of Pleistocene marine terraces. Similarly, San Diego Bay represents extension across a large right (releasing) step-over, where the majority of the Rose Canyon slip steps westward to the Descanso fault off northern Baja California (Figure 2). A consequence of this step is a minor component of normal faulting along the La Nacion fault zone, located east of the dextral fault zone, as well as transtensive faulting in San Diego Bay itself (see Gingery et al., 2010, this volume). The La Nacion fault is only expressed in the geology and topography adjacent to where the Rose Canyon fault bends south and steps to the Descanso fault. Although not proven definitively active, the La Nacion fault is part of the Rose Canyon deformation and, by nature of its sense of slip and structural ties to the Rose Canyon fault, likely continues to accommodate minor extension associated with the San Diego Bay step-over. One possible reason that geologists have not found definitive proof of its Holocene activity is that the discrete motion on the La Nacion fault is expected to be small on an event by event basis, so its expression in the active soil could easily be obscured.

The Rose Canyon fault is believed to have begun motion in the late Pliocene (Ehlig, 1980), although absolute constraints place it as post-Eocene and pre-late Pliocene based on the observation that the Upper Pliocene San Diego Formation Pleistocene (Demere, 1982). Thus, strata of the San Diego Formation may span several million years in age, which is expected if part of the strata accumulated in an active tectonic setting.

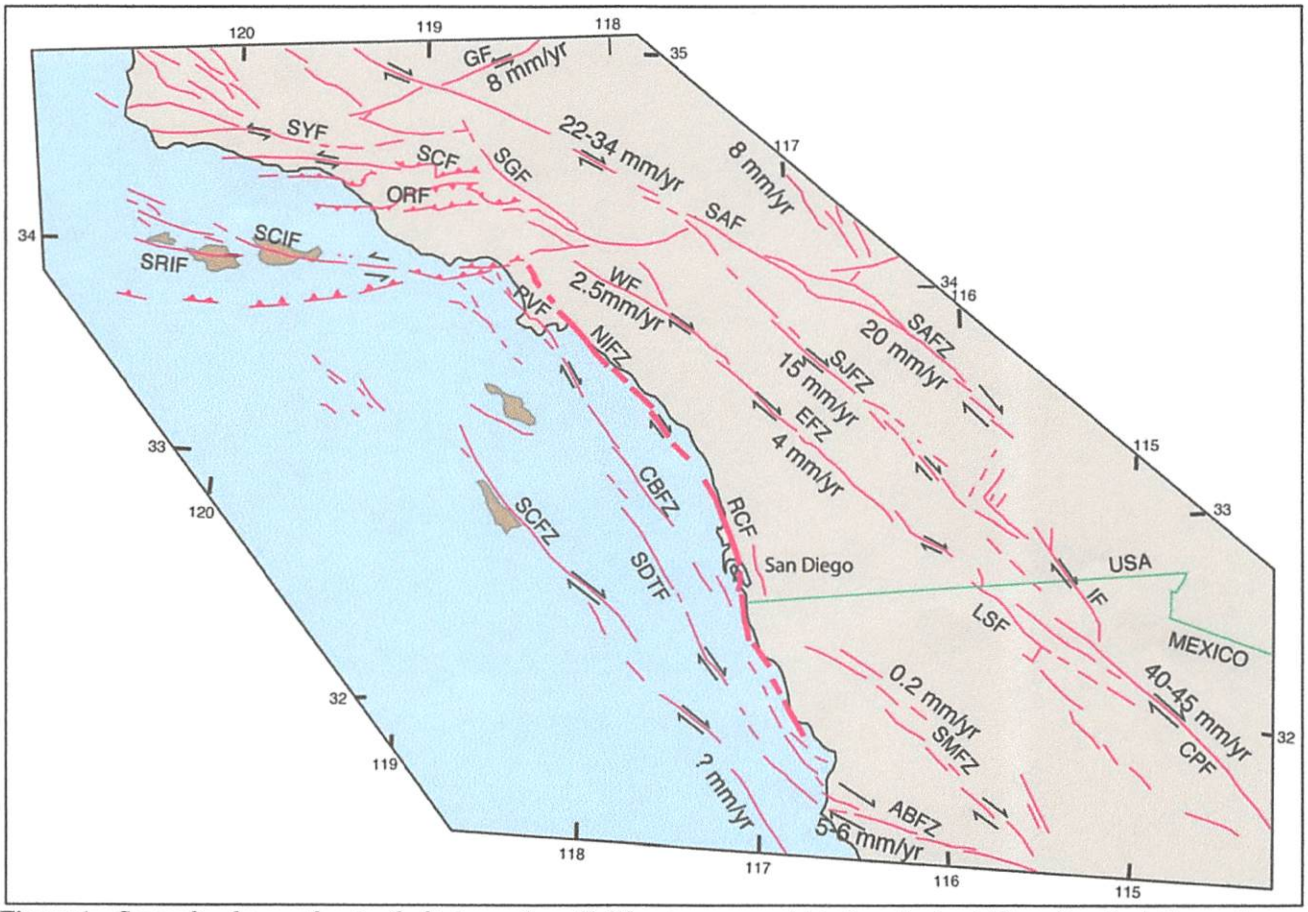

Figure 1. *Generalized map of major faults in southern California, across which there is about 50 mm/yr of relative motion. The Rose Canyon Fault (RCF) is bolded. Other faults are as follows: SAFZ = San Andreas Fault Zone, SJFZ = San Jacinto Fault Zone, EFZ = Elsinore Fault Zone, LSF = Laguna Salada Fault, CPF = Cerro Prieto Fault, ABFZ = Agua Blanca Fault Zone, SMFZ = San Miguel Fault Zone, IF = Imperial Fault, WF = Whittier Fault, PVF = Palos Verdes Fault, ORF = Oak Ridge Fault, SCF = San Cayetano Fault, SGF = San Gabriel Fault, SRIF = Santa Rosa Island Fault, SCIF = Santa Cruz Island Fault, SYF = Santa Ynez Fault, GF = Garlock Fault, SDTF = San Diego Trough Fault, SCFZ = San Clemente Fault Zone. CBFZ = Coronado Banks Fault Zone*

appears less deformed than the Eocene rocks (Kennedy et al., 1975b). Ehlig (1980) interpreted the Pliocene Embayment as a direct consequence of the initiation of the Rose Canyon fault, and it is into this embayment that the San Diego Formation accumulated. If correct, at least the upper member of the San Diego Formation is a tectono-stratigraphic unit that potentially records the history of motion of this fault.

The San Diego Formation is generally considered Pliocene in age, and analysis of foraminifera and calcareous nannoplankton mixed in with the classic molluscan index fossil *Patinopecten healeyi* indicate an age of 3.8-4.2 Ma for the lower member (Boettcher, 2001; Kling, 2001). The upper member has been suggested to be as young as early

Total displacement on the Rose Canyon fault is not well-resolved, but Kies (1982) suggests that facies within the Eocene Mt. Soledad Formation are offset about 4 km in a right-lateral sense. Similarly, Moore and Kennedy (1975) and Kennedy (1975) suggest several kilometers of right-lateral displacement based on the observation that the Pliocene San Diego Formation is found several kilometers farther north on the west side of the fault. They suggest that as much as 4-6 km of displacement has occurred on the northern margin of this Pliocene embayment.

Combining the 4-6 km estimates of displacement with the ~4 Ma maximum age of the San Diego Formation yields a minimum lifetime slip rate for the fault of about 1 mm/yr.

This minimum rate is in agreement with the minimum Holocene rate, as discussed below. A more reasonable lifetime

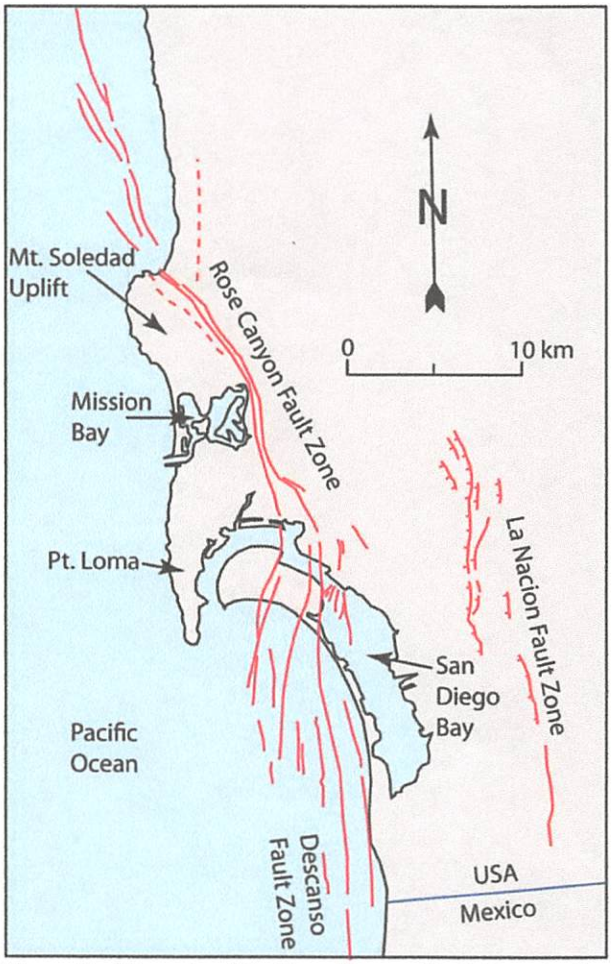

Figure 2. *Elements of the Rose Canyon Fault Zone in the San Diego Region.*

rate is to accommodate the 4-6 km of displacement since the late Pliocene, which yields a slip rate closer to 2 mm/yr. In any case, the current rate is more significant in terms of local hazard estimates, as discussed below.

GEOMORPHIC EXPRESSION

The Rose Canyon fault is well-expressed in the landscape of San Diego. The transpressive bend at La Jolla has produced uplift of Mt. Soledad, and the transtensive step has down-dropped the area of San Diego Bay. In fact, without the Rose Canyon fault, San Diego would never have had the World-class natural harbor that led to its' development into a World-class city.

On a finer scale, Lindvall and Rockwell (1995) analyzed early aerial photography from the 1920's to 1940's that predate the major expansion of the City after World War II. They found abundant evidence of youthful faulting between La Jolla and the San Diego River in the form of deflected and offset stream channels, small pressure ridges, a sag depression, and a scarp

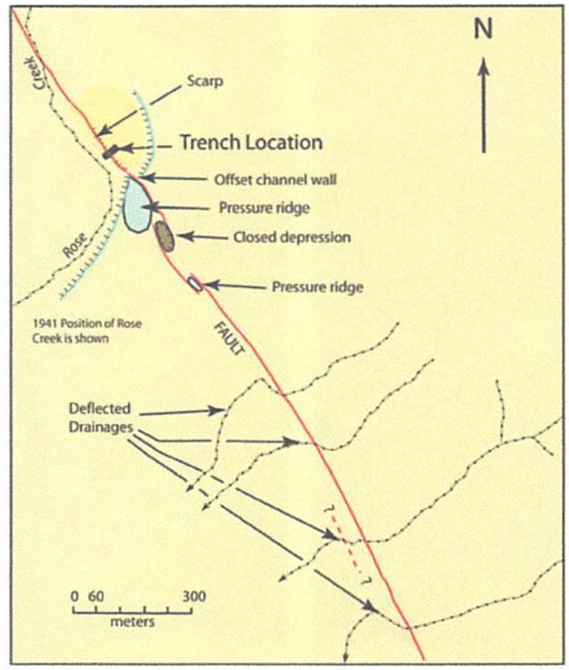

Figure 3. *Tectonic geomorphic features near Rose Creek that are interpreted to be the result of late Quaternary fault activity.*

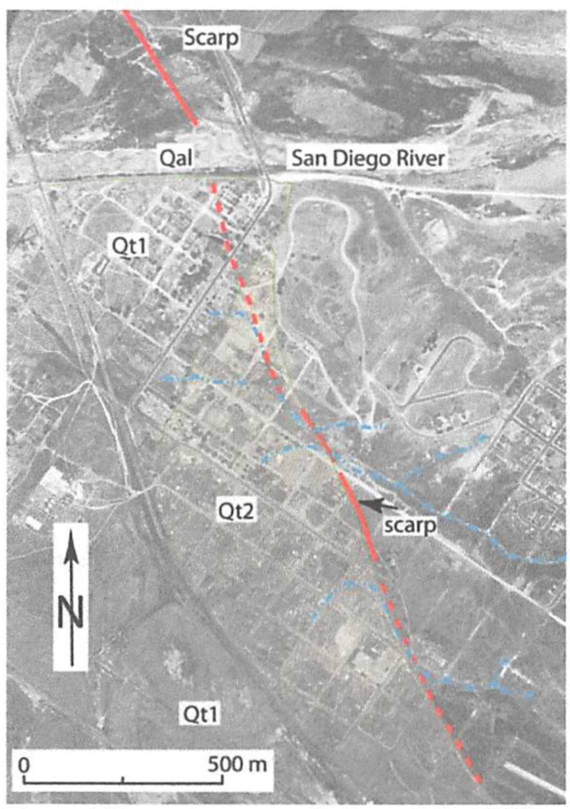

Figure 4. *Tectonic geomorphology of the Old Town strand of the Rose Canyon fault in Old Town, San Diego. Note that the deflected streams incise into the last interglacial marine terrace (Qt2).*

across the Holocene terrace to Rose Creek. Figure 3 shows a few of these features in the area near their trench, and Figure 4 shows deflected drainages and scarps interpreted from 1928 aerial photography in the Old Town area. Based on its geomorphic expression alone, the Rose Canyon fault is an active strike-slip fault.

SLIP RATE

The geologic late Quaternary slip rate of the Rose Canyon fault is derived from both short and long-term measurements. Lindvall and Rockwell (1995) excavated twelve trenches in a 3-dimensional excavation on a low terrace to Rose Creek and exposed a small gravel-filled channel that was radiocarbon dated to younger than 8.1 ka (calibrated years B.P.) The lateral excavations exposed remnants of the displaced channel across several strands of the fault in a 3 m-wide zone, but the unit containing the gravel was cut out by grading west of the fault (the site was graded and buried by up to 2.5 m of mechanically-emplaced fill in 1960). Consequently, Lindvall and Rockwell (1995) resolved only a minimum of 8.7 m of right-lateral displacement for the past 8.1 ka (maximum age), yielding a minimum Holocene slip rate of about 1.1 mm/yr. Furthermore, their study was conducted on the Mt. Soledad strand of the Rose Canyon fault zone, so this is a gross minimum for the entire zone if other strands are also active. Indeed, the Country Club strand is seen as a lineament crossing the Holocene terrace to Rose Creek in 1928 photography (Figure 5), and the Rose Canyon strand has not been trenched at this fault latitude. Considering this, Lindvall and Rockwell (1995) estimated the actual rate at 1.5±0.5 mm/yr, but with the upper limit on the rate being poorly constrained.

The stream deflections in Old Town, as shown in Figure 4, suggest a rate that is towards the high end of that suggested by Lindvall and Rockwell (1995). Several parallel channels are deflected at the fault by about 250±50 m. The channels incise a broad terrace surface which, based on its' elevation of 12-18 m, is likely the Nestor terrace equivalent (Kern and Rockwell, 1992). The Nestor terrace is well dated in San Diego at about 120 ka (Ku and Kern, 1974) and corresponds to the global highstand during oxygen isotope stage 5e (using the nomenclature of Shackleton and Opdyke, 1973). If the stream deflections accurately reflect lateral displacement along the fault, which is a reasonable interpretation, this resolves to a longer-term slip rate of about 2±0.4 mm/yr. This rate should be valid for the entire fault zone, as the streams cross the entire fault zone and the fault only splays into multiple strands south of Old Town.

TIMING AND SLIP IN PAST EVENTS

After the work of Lindvall and Rockwell (1995), quite a bit of new information has come to light on the Holocene history of faulting. Two sites, one in downtown San Diego and one in La Jolla, have yielded radiocarbon data that indicate that the most recent surface rupture on the fault has occurred in the past few hundred years (Rockwell and Murbach, 1996; Grant and Rockwell, 2002). Moreover, information collected during the 3-dimensional trenching study includes observations that relate to both timing and magnitude of past displacements. As the Lindvall and Rockwell (1995) paper focused primarily on the slip rate, one of the logs is presented here (Figure 6) and reinterpreted in relation to other useful information on timing and slip.

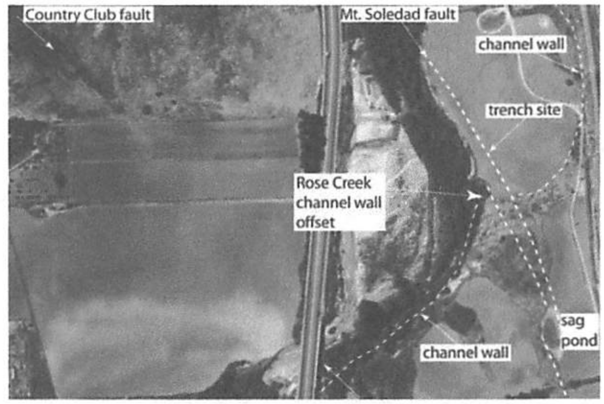

Figure 5. *1928 aerial photograph (Fairchild collection) showing the location of the Lindvall and Rockwell (1995) trench site on the Mt. Soledad strand. Note the vegetation lineament across the Holocene terrace to Rose Creek, suggesting that the Country Club fault may be active in this area. The Rose Canyon fault (sensu stricto) is off the photograph to the northeast.*

Figure 6 shows the log from the trench T4 exposure from the Lindvall and Rockwell's (1995) study. The channel that was used to resolve a minimum of 8.7 m of lateral displacement (Figure 7) is embedded in units C1 and C2 (Figure 6), but the actual top of the channel fill is near the top of unit C1. Thus, the age of the channel is best defined by the age of upper unit C1. This stratum did not yield any charcoal for radiocarbon dating, but the underlying unit C2 contained charcoal that yielded an age of ~8.6 ka (calibrated). However, unit C3 yielded a younger age of ~8.13 ka (calibrated), indicating that units C2 and C1 are younger than 8.1 ka. Lindvall and Rockwell (1995) argue that the actual age of the channel is likely close to 8.1 ka because all of the dates from units C2 and C3 are similar and because the soil separating these units is very weakly developed and cannot represent much time. Nevertheless, this date is still a maximum age for the units that host the gravel channel, so the resulting slip rate is a minimum value.

The soil that caps the deposits is moderately developed with an argillic horizon (Appendix, profiles RCF 1, RCF 2 and RCF 3, all of which were described in trench exposures on the northeast side of the fault). The alluvium into which the soil is developed contains abundant fines (silt and clay), so argillic horizons will form fairly rapidly in the coastal environment of

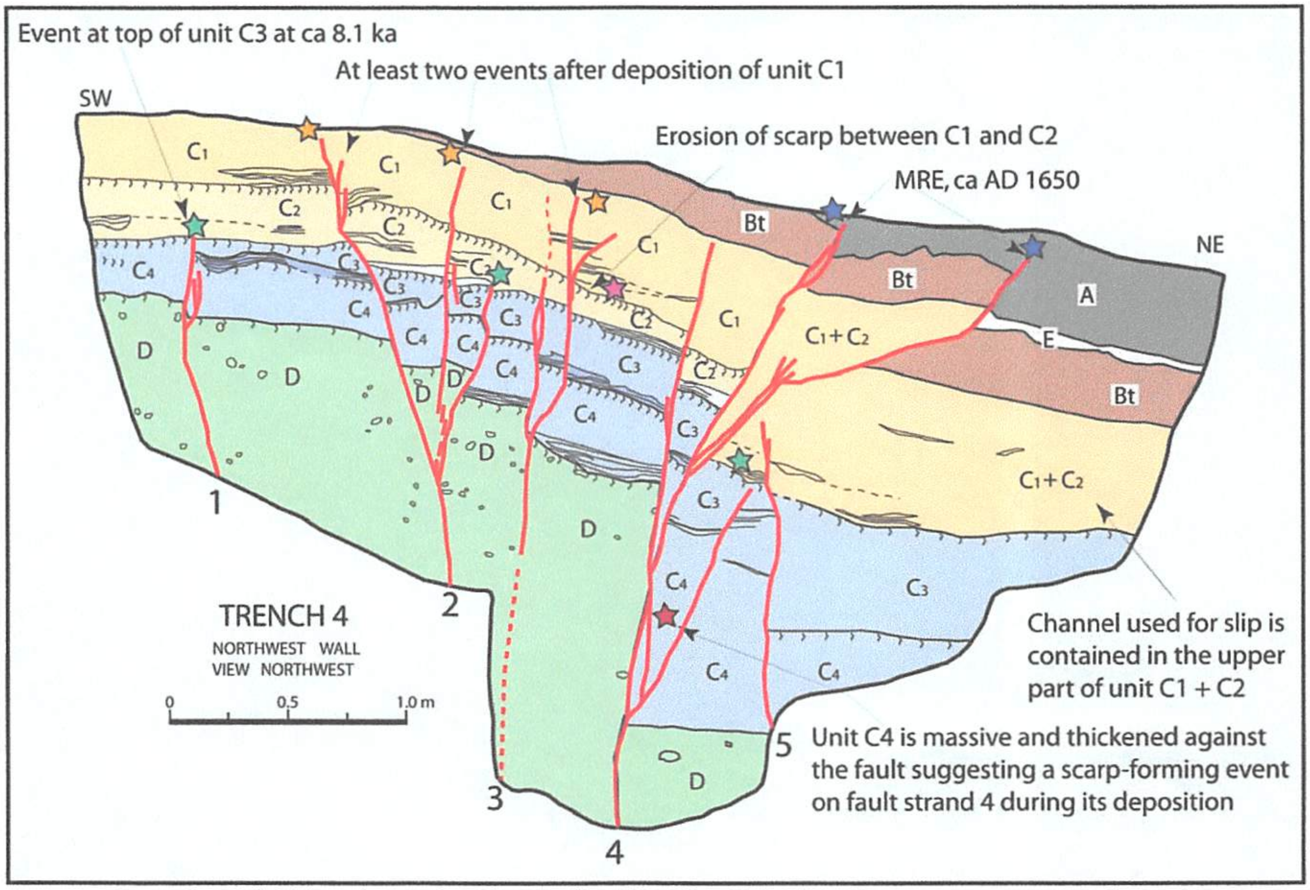

Figure 6. *Log of trench T-4, redrawn from Lindvall and Rockwell (1995). The stars represent evidence for past surface ruptures. The hatcher marks represent weakly formed topsoil (A) horizons. The upper, strongly formed soil is represented by the A, E and Bt horizons.*

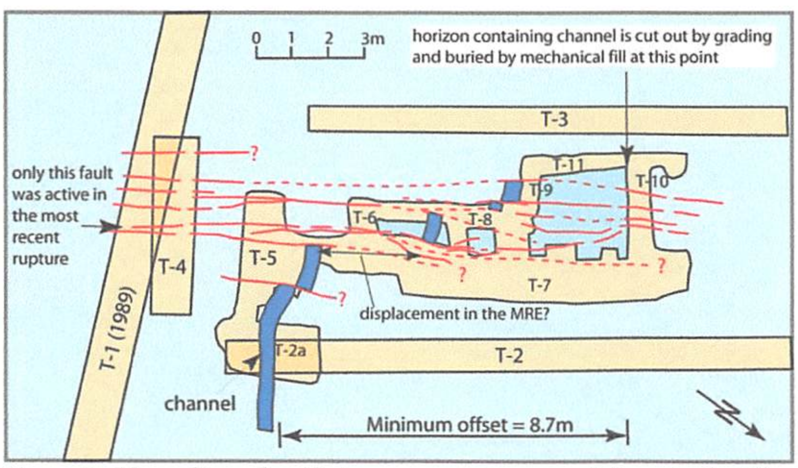

Figure 7. *Map of trenches that were used to map out the extent of the gravel channel embedded in units C1 and C2 (in blue). Note that the stratigraphic section that contained the gravel was graded out on the west side of the fault, presumably during grading of the site in 1960. Consequently, the lateral displacement of 8.7 m is a minimum value.*

southern California due to the presence of abundant sodium (Rockwell et al., 1985; Rockwell, 2000). Nevertheless, this argillic horizon had common thin to moderately thick clay films and moderately-developed structure, which represents significant development requiring many thousands of years of time for its formation. Comparison of the soil development index (SDI)(Harden, 1982) for these profiles to dated soils elsewhere in coastal southern California (Rockwell et al., 1985; and unpublished data) suggests 5-10 ka for the age of this soil, although the radiocarbon dates from the underlying stratigraphy require the soil to be less than 8 ka. For the purposes of this study, a minimum age of about 5 ka is assigned to the surface soil capping the faulted stratigraphy at Rose Creek. This point is important in understanding the timing of ruptures along the fault.

The log of trench T4 also contains direct evidence of several surface ruptures during the period of deposition of the section. Several fault strands (strands 1, 2, 3 and the western strand of fault 4, as indicated on Figure 6) all appear to have ruptured during an event that occurred between deposition of units C3 and C2, as indicated by the green stars in Figure 6. These fault strands have splays that are terminated and capped by unfaulted stratigraphy, and there is alluvium or colluvium of unit C3 that is truncated at fault strand 1. As the age of unit C3 has been determined to be about 8.1 ka by radiocarbon dating (Lindvall and Rockwell, 1995), this event must have occurred at or very soon after that time.

An earlier event during deposition of unit C4 is suggested by the dramatic increase in thickness of unit C4 across fault strand 4: this relationship was observed in many exposures. The massive (colluvial) character of unit C4 east of the fault, along with the observation that the thickness of unit C4 tapers away from fault strand 4, support the idea that an event with some vertical displacement occurred during deposition of unit C4, and that unit C4 is, in part, a colluvial wedge of material shed from the scarp. If correct, this event occurred between deposition of units D and the top of C4, both of which yielded radiocarbon ages of about 9.3 ka (calibrated), so an age of ~9.3 ka is assigned for this event.

Unit C2 is degraded and observed to thin across the scarp between fault strands 1 and 4 (magenta star in figure 6), and unit C1 has finely bedded strata that appear to have been deposited in angular unconformity against a scarp between fault strands 2 and 3. As unit C2 also contains finely-bedded strata, this unit cannot be interpreted as a colluvial deposit, and the thinning therefore most likely represents erosion across the scarp after slip occurred on the fault. Thus, a surface-rupturing event that produced some vertical displacement is interpreted to have occurred after deposition of unit C2 and before deposition of unit C1.

These observations argue that as many as three surface ruptures may have occurred on the fault during deposition of units C4 through the base of C1, and all of these apparently occurred in the early Holocene in a fairly narrow window of time. Further, as the channel that was used to resolve slip is embedded in unit C1, none of these events contributed to the 8.7 m of displacement documented by Lindvall and Rockwell (1995).

Fault strands 2, 3 and 4 all have elements that die upward into unit C1 and do not displace the capping soil, including the well-formed Bt horizon, as indicated by the orange stars in figure 6. This observation requires one or more surface ruptures to have occurred between deposition of unit C1 (and the gravel channel) and the development of the soil, and these ruptures produced offset of the gravel channel embedded near the top of unit C1. In figure 7, these fault strands produced at least 5.7 m of cumulative lateral displacement, based on offset of the channel. The timing of these displacements are poorly constrained, but the fact that the soil is developed across these strands and is not offset by them indicates that none of these faults have likely moved in many thousands of years, and possibly not since soon after deposition of the section and the onset of soil development.

In contrast, the eastern two strands of fault 4 sharply offset the surface soil, including the topsoil (A) horizon. Reconstructing the vertical separation of the Bt, C1 and C2 horizon suggest that all are vertically displaced by the same amount, and this relationship was observed in many exposures during the 3D trenching. This, in turn, argues that a single rupture produced this deformation because multiple events should have sustained erosion and deposition of colluvium between ruptures unless there was essentially no time to allow for such erosion. As erosion of a scarp can begin within the first winter after a scarp-forming event, and as there is no evidence for such an event, it is likely that this displacement represents only a single slip surface rupture.

This has important implications from two perspectives. First, the most recent rupture appears to follow a rather lengthy period of time, as significant time is required to have allowed the soil to develop to its current state. After soil development, it appears that only the most recent event has produced slip on

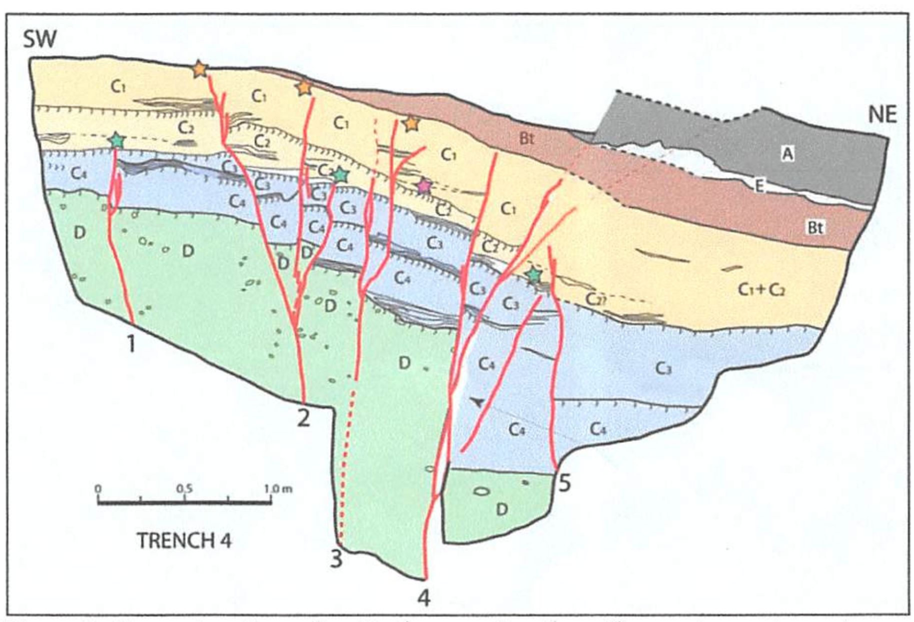

Figure 8. *Reconstruction of vertical separation from the most recent event, as exposed in trench T4. Note that the dominant sense of slip is right-lateral, as exposed in the lateral trench excavations of figure 7, so units may not match perfectly. Nevertheless, units C1 and C2 realign very well when the vertical separation associated with the modern soil is removed, suggesting that this represents a single displacement after the end of unit C1 deposition.*

the Mt. Soledad strand of the Rose Canyon fault zone, which is interpreted as the primary strand of the Rose Canyon system at this fault latitude as it is best expressed in the geomorphology. Thus, from the perspective of earthquake recurrence, there appears to have been a cluster of events in the early Holocene followed by many thousands of years of inactivity and soil development until this recent surface rupture.

The timing of this most recent event is well-described by Rockwell and Murbach (1996) and Grant and Rockwell (2002) as after AD 1523 and before the construction of the first mission in San Diego in 1769. The construction of the mission precludes a large earthquake after that time, as a surface rupture in San Diego would assuredly have destroyed the mission, and there is no record of such an event. Thus, the event has been assigned a date of ~AD 1650±120 years.

The other aspect of significance with the soil observations is that the most recent rupture broke only the eastern strands of fault 4 (Figure 6). The reconstruction in Figure 8 suggests that this may be the only event to have ruptured these strands between the deposition of units C1 and C2 and the development of the surface soil, as they are all vertically displaced the same amount, within resolution, and this relationship was seen repeatedly in multiple exposures. The map in Figure 7 shows that these strands have produced 3 m of post channel slip, which implies post unit C1. Taken together, these observations argue that all 3 m of this displacement occurred in the most recent event in ca AD 1650. Considering that the channel is offset at least an additional 5.7 m by fault strands that did not rupture in the most recent event, a simple interpretation is that there have been at least two additional, similar-sized (3 m) events after the end of deposition at the site, or sometime after 8.1 ka. Again, these events must have occurred in the early Holocene to allow sufficient time to develop the surface soil that appears to be offset by only the most recent event.

Discussion and Conclusions

Paleoseismic work along the onshore Rose Canyon fault zone in the City of San Diego clearly demonstrates that the fault has sustained recurrent Holocene activity (Lindvall and Rockwell, 1995; Rockwell and Murbach, 1996; Grant and Rockwell, 2002). However, more detailed analysis of existing paleoseismic data suggests that the fault underwent a cluster or burst of activity in the early Holocene, followed by a relatively long period of inactivity during which soil formation occurred across the early Holocene fault strands. Figure 9 summarizes the information on the timing and displacement associated with these Rose Canyon events. In this figure, it is assumed that the moderately developed surface soil represents at least 5,000 years of stability and development, and that its' offset is the result of only the most recent event because it is so cleanly displaced. In the most recent event, which is dated in La Jolla and downtown San Diego as being in the past few hundred years but pre-mission period, we attribute the entire 3 m of displacement associated with the faults involved in this rupture. If some of the displacement occurred during earlier events, then the measured slip is less for the most recent event but must be increased for earlier ones. In that the gravel-filled channel is displaced by at least an additional 5.7 m, it seems reasonable that this displacement occurred in an additional two events that were similar in size to the most recent event. Alternatively, there may have been many smaller events that cumulatively produced these observed displacements, but that makes the long hiatus in slip that is evident from the soil development even more problematic. It therefore seems simplest to interpret these data as the result of three relatively large (~3 m) displacements in the period after the end of deposition of unit C1 (post-8.1 ka). This implies that these earthquakes were likely at least M7 in magnitude. If these are average values for displacement in these past events, a magnitude of M_w7.3 is calculated using the regressions of Wells and Coppersmith (1994).

The earlier events are derived from the trench data in Rose Creek. Two events (orange stars) are interpreted to have occurred after deposition of the gravel channel of unit C1 because at least 5.7 m of displacement can be attributed to the

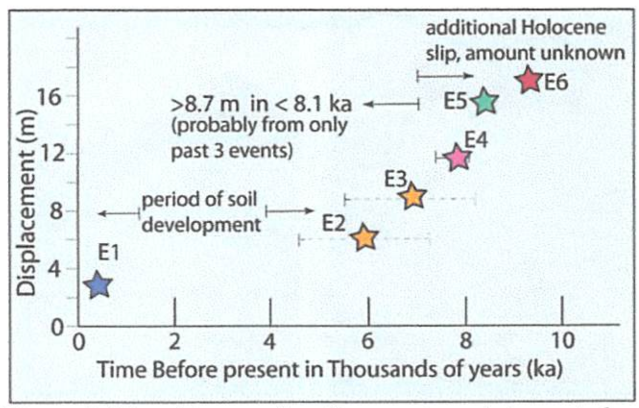

Figure 9. *Time history of surface ruptures interpreted from the paleoseismic information collected for the Rose Canyon fault in the City of San Diego. Six surface ruptures are interpreted from the trench exposures in Rose Creek (using data collected in the 1992 excavations of Lindvall and Rockwell, 1995), with the most recent event date from La Jolla and downtown San Diego (Rockwell and Murbach, 1996; Grant and Rockwell, 2002). The colored stars correspond to the event horizons identified in figure 6. The displacement values are derived from figure 7, where displacement is only known for the past three events. The strongly-formed soil is interpreted to represent at least 5 ka of development time, although there are no direct measurements to corroborate this estimate. It is possible that additional ruptures have occurred at this site for which there is no evidence due to lack of deposition, so the inferred recurrence interval is a maximum value.*

fault strands that were active in this period, as discussed above, and this is nearly twice that which occurred in the most recent event. Alternatively, the penultimate event could have been substantially larger, although this interpretation seems less likely as the Rose Canyon fault is only about 40 km in length if one considers the major step-overs in San Diego Bay and near Oceanside.

Events 4, 5, and 6 are recorded in the floodplain sediments of Rose Creek. The earliest of these (Red star in Figures 6 and 9) is well-dated at about 9.3 ka (in unit C4). Event 5 (green star in figures 6 and 9) appears to have broken all fault strands and occurred soon after 8.1 ka. Event 4 (magenta star) also occurred soon after 8.1 ka if Lindvall and Rockwell's (1995) interpretation is correct that the very weak top-soil horizons between deposition of units C1 through C4 represent only a short amount of time.

Considering that the surface soil represents a long period of stability, it is not possible to simply space the timing of all six events equally for the past 9.3 ka. In fact, if the interpretation is correct that the surface soil represents at least 5 ka of development, then five of these events occurred as a cluster in the period between about 9.3 and 5 ka, with an average interval of recurrence of less than 1 ka. This observation of clustering is similar to many faults Worldwide, including the San Jacinto and San Andreas faults in southern California (Fumal et al., 2002; Rockwell et al., 2006, 2008), the Wasatch, New Madrid and Meers fault in the mid-continent region of the US, the Vilarica fault in Portugal (Rockwell et al., 2009), and the North Anatolian fault in Turkey (Okumura et al., 2009 in review). For the San Jacinto record of 18 surface ruptures at Hog Lake (Rockwell et al., 2008, 2009), the fault has mode-switched from clustered to periodic behavior, but without much predictability as to when such a change in behavior will occur.

For the Rose Canyon fault, its Holocene behavior can be interpreted in several ways, each with its own implications for seismic hazard. The average return period for large surface ruptures during the Holocene is about 1800 years if one simply takes the occurrence of six events (5 intervals) in the past 9.3 ka. However, using the limited timing information at hand suggests that five of these events (4 intervals) occurred in a ~3 ka period, yielding a much shorter return period within the cluster of about 800 years. Further, events 2 through 5 may have occurred in as little a couple thousand years if the surface soil represents as much as 5000 years of development. If the fault principally behaves in a clustered seismicity mode, and if the five early Holocene events represent such a cluster, then one must consider the possibility that the recent earthquake of ca. AD 1650 represents a return to activity and is possibly the first in the next cluster of large earthquakes.

In the first case where earthquakes are assumed to be quasi-periodic in their recurrence, the conditional probability of the occurrence of another M7+ Rose Canyon rupture has a likelihood of less than 1% when the lapse time of only a few hundred years is used. In the second scenario, the probability increases dramatically if we have entered another cluster, because the interval between events within a cluster is much shorter than the long-term average. Additional work on the discrete timing of each Holocene surface rupture is warranted to better constrain the behavior of the Rose Canyon fault, as well as to assign more realistic probabilities for the occurrence of future large earthquakes in America's Finest City.

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