A Northward-propagating Earthquake Sequence in Coastal Southern California?

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INTRODUCTION

The devastating 1999 *M* 7.4 Izmit, Turkey earthquake was "no surprise" (Reilinger *et al.*, 2000) because it occurred as part of a sequence of earthquakes that have ruptured nearly the entire length of the strike-slip North Anatolian Fault zone (> 1,000 km) since 1912. The 1999 rupture occurred on a segment previously identified as a seismic gap (Toksöz *et al.*, 1979) and recently studied to understand mechanisms of stress transfer and earthquake triggering along strike-slip faults (Stein *et al.*, 1997). We suggest that an analogous rupture sequence spanning the last few centuries may be in its later stages along southern California coastal faults.

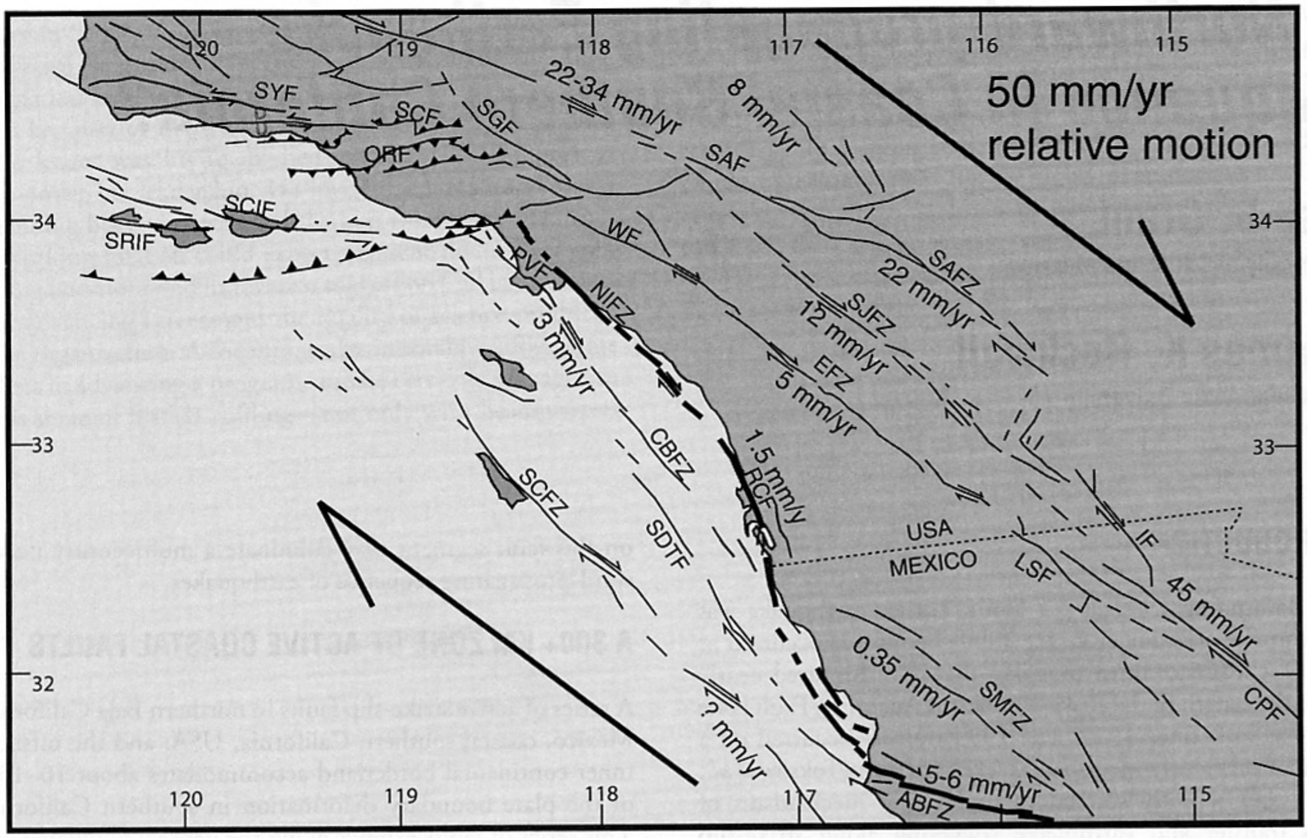
As we will discuss, recently published fault investigations in the northern Baja California peninsula (México) and coastal southern California (USA) reveal evidence for geologically contemporaneous or sequential earthquakes along a > 300-km-length, predominantly strike-slip seismic zone. This coastal fault zone includes structures previously mapped as the Agua Blanca, Rose Canyon, San Joaquin Hills, and southern Newport-Inglewood Fault zones (Figures 1 and 2). Radiocarbon dating and the historic record indicate that moderate to large earthquakes occurred after A.D. 1640 ± 160, 1523 to 1769, and 1635 to 1855 on the Agua Blanca Fault (Rockwell *et al.*, 1993), on the Rose Canyon Fault (Rockwell and Murbach, 1999), and in the San Joaquin Hills (Grant *et al.*, 2002), respectively. Additionally, a moderate to large ($M \geq 6.5$) earthquake is interpreted for the near offshore region in A.D. 1800 based on historical accounts (Toppozada *et al.*, 1981). Finally, a M_w 6.4 earthquake on the southern Newport-Inglewood Fault zone (NIFZ) followed in 1933 (Barrows, 1974; Hauksson and Gross, 1991) and increased the Coulomb stress on the northern NIFZ in Los Angeles (Stein *et al.*, 1994). The date of last surface rupture of the northern NIFZ is not known (Bryant, 1988), although it is zoned as an active fault by the state of California. An energetic sequence of moderate magnitude earthquakes in late 2001 (Hauksson *et al.*, 2002) suggests the possibility that the northern NIFZ is close to failure and that a future earthquake on this fault segment may culminate a multicentury northward-propagating sequence of earthquakes.

A 300+ KM ZONE OF ACTIVE COASTAL FAULTS

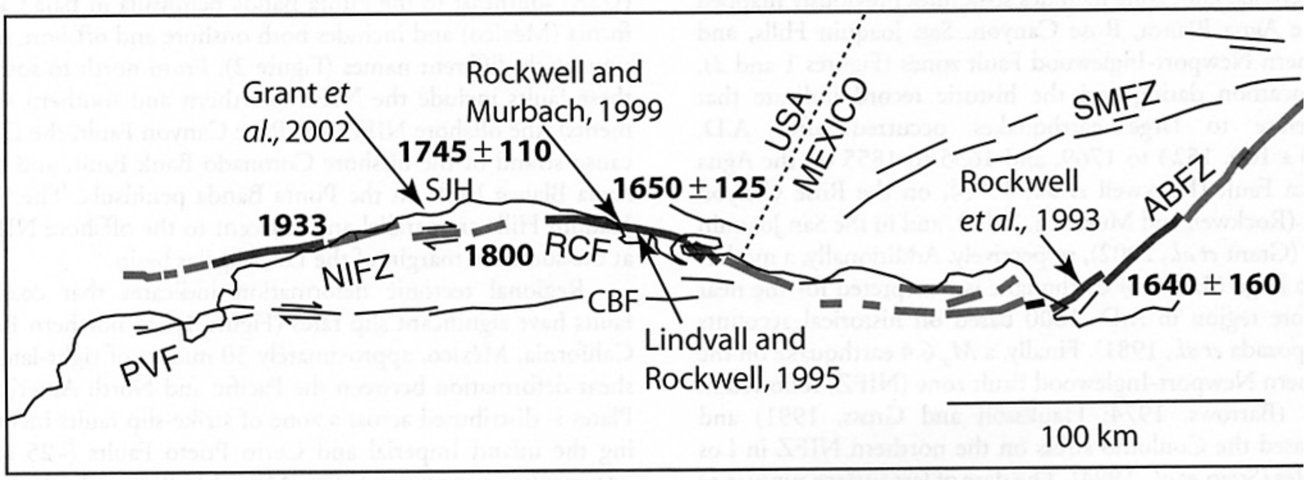
A series of active strike-slip faults in northern Baja California, México, coastal southern California, USA; and the offshore inner continental borderland accommodates about 10–15% of the plate boundary deformation in southern California. This series of faults extends along the densely populated and scenic coastline (Bennett *et al.*, 1996). Seismic hazard associated with these faults has been recognized for decades (Barrows, 1974) but is still poorly quantified (SCECWG, 1995) due, in part, to the difficulty of integrating observations onshore and offshore.

We focus on a > 300-km-length zone of faults that appear to be kinematically linked. At a minimum, the Coastal Fault Zone extends from Beverly Hills, California (USA) southeast to the Punta Banda peninsula in Baja California (México) and includes both onshore and offshore sections with different names (Figure 2). From north to south, these faults include the NIFZ (northern and southern segments), the offshore NIFZ, the Rose Canyon Fault, the Descanso strand of the offshore Coronado Bank Fault, and the Agua Blanca Fault on the Punta Banda peninsula. The San Joaquin Hills are parallel and adjacent to the offshore NIFZ at the southern margin of the Los Angeles basin.

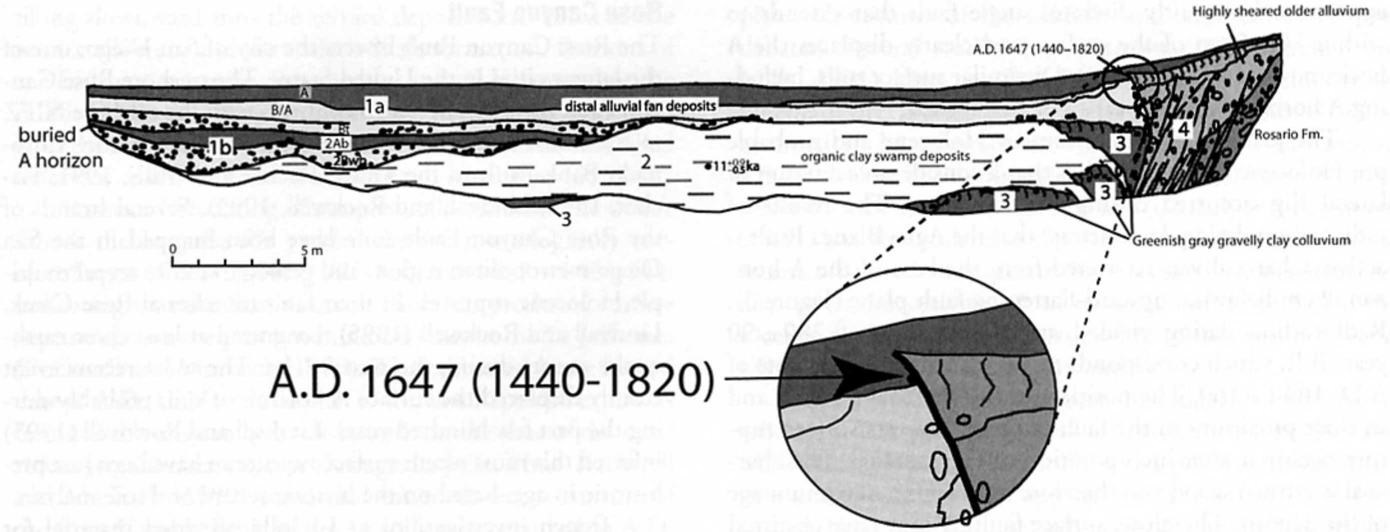
Regional tectonic deformation indicates that coastal faults have significant slip rates (Figure 1). In northern Baja California, México, approximately 50 mm/yr of right-lateral shear deformation between the Pacific and North American Plates is distributed across a zone of strike-slip faults including the inland Imperial and Cerro Prieto Faults (~25 and ~45 mm/yr, respectively), San Miguel-Vallecitos Fault zone (~0.35 mm/yr), and coastal Agua Blanca Fault zone (5–6 mm/yr) (Rockwell *et al.*, 1993; Hirabayashi *et al.*, 1996; Bennett *et al.*, 1996; Walls *et al.*, 1998). In southern California, the deformation is distributed across a zone of strike-slip faults including the southern San Andreas Fault (~22 mm/yr)



▲ **Figure 1.** Map of major faults in southern California (USA) and northern Baja California (México) including the offshore strands. Faults are annotate geologically measured slip rates where available. Major faults include the San Andreas Fault and zone (SAF and SAFZ), San Jacinto Fault zone (SJFZ), El Fault zone (EFZ), Whittier Fault (WF), Palos Verdes Fault (PVF), Newport-Inglewood Fault zone (NIFZ), Rose Canyon Fault (RCF), Agua Blanca Faul (ABFZ), San Miguel Fault zone (SMFZ), Imperial Fault (IF), Cerro Prieto Fault (CPF), and Laguna Salada Fault (LSF). Offshore faults include the Cor Bank Fault zone (CBF), San Diego Trough Fault (SDTF), San Clemente Fault zone (SCFZ), Santa Cruz Island Fault (SCIF), and Santa Rosa Island Fault (The San Gabriel Fault (SGF), San Cayetano Fault (SCF), Oak Ridge Fault (ORF), and Santa Ynez Fault (SYF) are located in the Transverse Ranges. Mo from Walls *et al.* (1998) and other sources.



▲ **Figure 2.** Map of the Coastal Fault Zone with dates of most recent rupture and reference to previous studies. From north (left) to south (right), the C Fault Zone includes the northern Newport-Inglewood Fault zone (NIFZ; unknown date of last rupture), southern NIFZ (source of the 1933 Long Beach quake), San Joaquin Hills (SJH; elevated by a $M > 7$ earthquake), the offshore NIFZ (possible source of the 1800 earthquake), Rose Canyon Fault (RCF tions of trench sites indicated by arrows), Coronado Bank Fault (CBF), and Agua Blanca Fault zone (ABFZ; arrow indicates study site location). Modifie Walls *et al.* (1998), Grant *et al.* (1997, 2002), Lindvall and Rockwell (1995), and Rockwell and Murbach (1999).



▲ **Figure 3.** Simplified trench log from the El Mirador EM-1 trench site on the Agua Blanca Fault. See text for explanation. Modified from Rockwell *et al.* (1993).

and faults of the Peninsular Ranges and offshore Inner Borderlands provinces (Bennett *et al.*, 1996). Geologically measured slip rates of the southern San Jacinto Fault (12 mm/yr), Elsinore Fault (5 mm/yr), and Rose Canyon Fault (1.5 mm/yr) decrease west of the San Andreas Fault and are generally consistent with velocities of GPS stations in the SCIGN network (Walls *et al.*, 1998). A complex zone of offshore faults, including the Coronado Bank Fault, San Diego Trough Fault, and San Clemente Fault, are tectonically active (Legg, 1991; Dixon *et al.*, 2000). GPS measurements indicate that approximately 14% of the total Pacific-North America Plate motion occurs west of the Elsinore Fault, most likely distributed across the San Clemente, Newport-Inglewood, Rose Canyon, and other coastal or offshore faults (Bennett *et al.*, 1996).

HISTORIC AND PALEOSEISMIC ACTIVITY

Historic seismicity and paleoseismic investigations reveal that the Coastal Fault Zone is active and has generated several large earthquakes within the last few centuries. Previous studies have focused on individual faults or specific sections of the Coastal Fault Zone rather than examining the zone in its entirety. Individually, the coastal faults have lower slip rates and longer recurrence intervals than many onshore faults and therefore are calculated to represent relatively low hazard (*e.g.*, SCECWG, 1995). However, if we examine the entire zone, we find that it ruptured most recently in a temporal cluster or propagating sequence of large earthquakes. Therefore the hazard may be high if the sequence or cluster is still in progress. In the following sections, we summarize available data on seismicity and rupture history of the Coastal Fault Zone and consider the potential for a future rupture.

Agua Blanca Fault

The northwestern Baja California peninsula is cut by two major fault zones: the Agua Blanca Fault and the San Miguel-Vallecitos Fault. The Agua Blanca Fault is the dominant transpeninsular fault in northern Baja California, México (Rockwell *et al.*, 1993). South of San Diego and Mission Bay, the Rose Canyon Fault zone connects with the Agua Blanca Fault via a zone of offshore faults that transfer slip to the onshore Agua Blanca Fault at Punta Banda, México (Andersen *et al.*, 1989; Lindvall and Rockwell, 1995). The San Miguel Fault has a relatively low slip rate of approximately 0.2 mm/yr (Hirabayashi *et al.*, 1996) but has abundant microseismicity and a historic record of seven or eight earthquakes over M 6, including six M 6–6.8 earthquakes between 1954 and 1956 (Andersen *et al.*, 1989). Trenches across the 1956 surface rupture revealed only two ruptures within the past 600 years, following a 10,000 year interval with no recognizable surface displacement (Hirabayashi *et al.*, 1996). The surface rupture record is consistent with the low slip rate, making the high rate of historic seismicity surprising. In contrast, the Agua Blanca Fault zone has been relatively quiet historically but has a late Quaternary to early Holocene slip rate of 4–6 mm/yr (Rockwell *et al.*, 1993).

The most recent rupture of the Agua Blanca Fault zone was investigated by excavating a trench at the El Mirador site (EM-1) in the Punta Banda Ridge study area southwest of the Punta Banda peninsula. Results of this study are documented in Rockwell *et al.* (1993) and summarized herein.

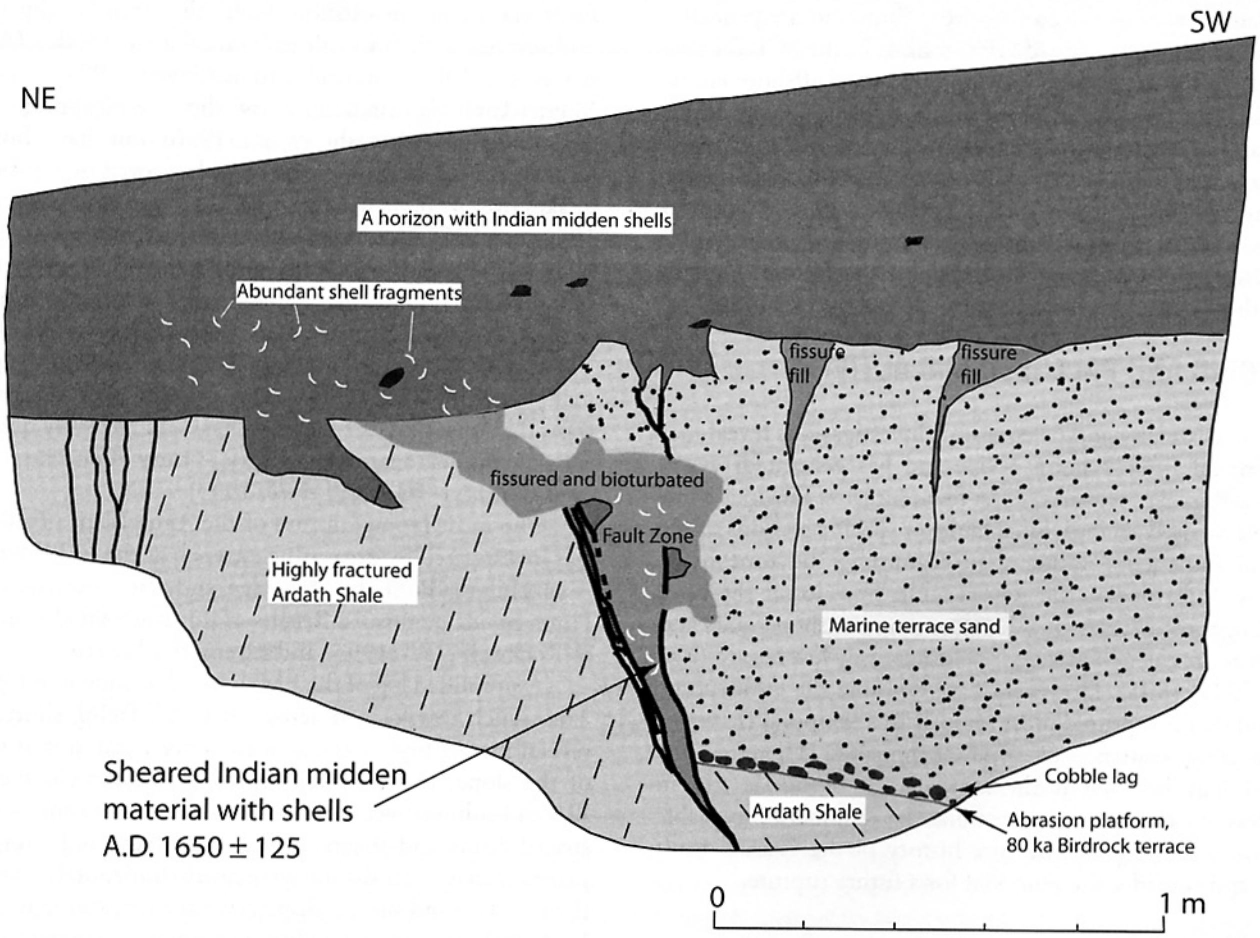
A simplified log of the EM-1 trench is shown in Figure 3. The trench was located across an uphill-facing shutterridge several meters high and extended across a flat area at the toe of the slope. In the lower depths of the trench, the Agua Blanca Fault was well expressed as a 3-m-wide zone of closely spaced faults and shears. Slickensides measured along fault planes in clayey sandstone were nearly horizontal, raking less than 5°. Ground surface displacement along the Agua Blanca Fault in this trench generally appears to be restricted to a zone less than 3 m wide. Dissimilar colluvial wedges are juxtaposed by presumably significant strike-slip displacement along what appears to be a fairly discrete, single fault that extends to within 10–15 cm of the surface and clearly displaces the A horizon of the soil (Figure 3). Dissimilar surface soils, including A horizons, also appear to be juxtaposed.

The juxtaposition of dissimilar Holocene and probable pre-Holocene age soils implies that a considerable amount of lateral slip occurred during the Holocene. The results of radiocarbon dating demonstrate that the Agua Blanca Fault is active. Charcoal was recovered from the base of the A horizon, 2 cm below an upward-flattening fault plane (Figure 3). Radiocarbon dating yielded an apparent age of 280 ± 90 years B.P., which corresponds to a dendrochronologic date of A.D. 1640 ± 160. The position of the charcoal beneath and in close proximity to the fault strongly suggests surface rupture occurred after incorporation of the charcoal. The charcoal is burned wood and therefore represents a maximum age of the deposit. Therefore, surface faulting may have occurred as recently as the historic period, although there are no large historical earthquakes to ascribe to this fault. Based on these observations, Rockwell *et al.* (1993) concluded that the most recent rupture of the Agua Blanca Fault occurred after a date within the range A.D. 1640 ± 160, or just before the start of the historic record.

Rose Canyon Fault

The Rose Canyon Fault bisects the city of San Diego, one of the largest cities in the United States. The onshore Rose Canyon Fault zone in San Diego connects with the offshore NIFZ to the north and the Descanso strand of the offshore Coronado Bank Fault to the south (Fischer and Mills, 1991; Fischer, 1992; Lindvall and Rockwell, 1995). Several strands of the Rose Canyon Fault zone have been mapped in the San Diego metropolitan region, and geologic studies reveal multiple Holocene ruptures. In their fault trenches at Rose Creek, Lindvall and Rockwell (1995) recognized at least three earthquake events during the past 8.1 ka. The most recent event cleanly displaced the surface A horizon of soil, probably during the past few hundred years. Lindvall and Rockwell (1995) inferred this most recent surface rupture to have been just prehistoric in age, based on the historic record and soil analysis.

Trench investigations at La Jolla provided material for radiocarbon dating of the most recent rupture. At the La Jolla trench site of Rockwell and Murbach (1999), the fault is visible through the topsoil, which contained an Indian midden deposit (Figure 4). The A horizon of the soil is approximately 40 cm thick in the area of the trench. The fault is generally less than 20 cm wide and is expressed as fissures with topsoil



▲ **Figure 4.** Simplified trench log from the La Jolla excavation site along the Rose Canyon Fault. See text for explanation. Modified from Rockwell and Murbach (1999).

filling downward into the terrace deposits and between the terrace alluvium and the Ardath Shale formation. Portions of the fault contact were disturbed by animal burrows, but the midden material was clearly displaced and shells associated with the midden were included in the soil material that filled fissures in the fault zone (Rockwell and Murbach, 1999).

Radiocarbon dating of samples collected from the fissure fills at the La Jolla site yielded dendrochronologically corrected ages of A.D. 1644 + 77/–160 and 1667 + 146/–144, indicating that the Rose Canyon Fault has produced surface rupture during the past few hundred years in the La Jolla area (Rockwell and Murbach, 1999). The calibrated lower bound date of A.D. 1523 and the year 1769, when Spanish explorers founded the mission, provide bounds on the date of the most recent large surface rupture through La Jolla. Thus, Rockwell and Murbach (1999) concluded the most recent rupture of the Rose Canyon Fault in the La Jolla area occurred in A.D. 1650 ± 125. This age is indistinguishable from the date estimated for the time of last rupture in the Rose Creek area (Lindvall and Rockwell, 1995) and agrees well with unpublished observations from consultants' trenches in downtown San Diego, where the most recent rupture was estimated to have occurred between A.D. 1420 and 1769 (Rockwell and Murbach, 1999).

Excavations at Rose Creek (Lindvall and Rockwell, 1995) provide observations for measuring displacement from the most recent earthquake. Rockwell and Murbach (1999) re-evaluated three-dimensional data from the Rose Creek site and concluded that the most recent earthquake produced approximately 3 m of slip. Therefore, the earthquake that ruptured the Rose Creek site was large enough to have ruptured strands at La Jolla, in downtown San Diego, and possibly beyond the San Diego area. We adopt the best constrained age of A.D. 1650 ± 125 from the La Jolla site as the age of the most recent Rose Canyon Fault rupture in the San Diego area and estimate that it was approximately a M 7 earthquake based on slip measurements and empirical relationships between magnitude and slip (Wells and Coppersmith, 1994).

Offshore Newport-Inglewood Fault Zone

The Rose Canyon Fault zone extends offshore at La Jolla and continues northward approximately parallel to the coast to Newport Beach, where it is mapped onshore as the NIFZ (Lindvall and Rockwell, 1985; Barrows, 1974; Morton and Miller, 1981). The offshore fault zone is often referred to as the offshore Newport-Inglewood Fault zone (Fischer and Mills, 1991; Fischer, 1992), although a variety of names have been employed by different investigators (Barrows, 1974). The offshore NIFZ is a structurally complex zone of folds and faults (Barrows, 1974; Fischer and Mills, 1991; Fischer, 1992). Scattered seismicity occurs along the zone, although events are difficult to locate accurately due to poor station coverage (Astiz and Shearer, 2000; Fischer and Mills, 1991).

The seismic potential of the offshore NIFZ was evaluated in the 1970's for design of the San Onofre nuclear power plant. Continuity of the offshore and southern NIFZ was debated. Several studies (*e.g.,* Barrows, 1974; Fischer and Mills, 1991) have concluded that they are continuous or kinematically linked, and therefore the offshore NIFZ is assumed to be seismogenic. An upper bound slip rate of 3.5 mm/yr has been estimated (Fischer, 1992) based on total offset with an estimated age of 2 Ma (Crouch and Bachman, 1989), but the Holocene slip rate is probably lower. More recent offshore investigations have focused on the structure and potential activity of a low-angle offshore fault, the Oceanside thrust, and its relationship to the offshore NIFZ (Rivero *et al.*, 2000; Bohannon and Geist, 1998).

The offshore NIFZ has been investigated with seismic reflection data and analysis of microseismicity. Fischer and Mills (1991) report a seismically active positive flower structure and thrust complex approximately 240 km long. Disturbed Holocene seafloor sediments are reported offshore Dana Point, San Onofre, Oceanside, and Del Mar. Microseismicity along the offshore NIFZ zone between 1932 and 1991 was an order of magnitude less than for the onshore NIFZ (Fischer and Mills, 1991). A small cluster of earthquakes along the zone near Oceanside in 1981 ($M < 3.0$) had strike-slip focal mechanisms, but elsewhere along the zone normal and thrust focal mechanisms have been reported (Fischer and Mills, 1991)

The date of most recent rupture of the offshore NIFZ is not known, although seismic-reflection observations and microseismicity indicate that it was during the Holocene. It may have ruptured early in the historic period. Spanish explorers traversed coastal southern California in 1769, and construction of the first mission building began shortly thereafter (Toppozada *et al.*, 1981). An earthquake on 22 November 1800 caused damage and was reported by Spanish missions in San Diego and San Juan Capistrano. No other observers were recording earthquakes along the coast during the early historic period, so the location and magnitude of the 1800 earthquake are poorly constrained. Toppozada *et al.* (1981) estimated a $M \geq 6.5$ and proposed a coastal or offshore location for the 1800 earthquake. If this interpretation is correct, the earthquake could have occurred on the offshore NIFZ.

San Joaquin Hills

The San Joaquin Hills (SJH) are located inland of the offshore NIFZ at the southern boundary of the Los Angeles basin (Morton and Miller, 1981). Several high-angle faults in the SJH may be strands of the ancestral NIFZ (Bender, 2000) and show evidence of Quaternary surface rupture (Grant *et al.*, 2000). Based on measurements of late Quaternary and Holocene uplift, the SJH have been interpreted to be underlain by an active blind thrust fault (Grant *et al.*, 1999, 2000, 2002). Movement of the SJH blind fault may be kinematically linked to the NIFZ (Grant *et al.*, 1999, 2000), the offshore Oceanside Fault (Rivero *et al.*, 2000), or both.

Late Holocene uplift of the San Joaquin Hills is evidenced by elevated marsh deposits in Newport Bay and a shoreline along the open coast that is 1 m to 3.6 m above the current shoreline (Grant *et al.*, 2002). The age of the marsh and historic seismicity bracket the age of uplift within the last few centuries. Radiocarbon dating of elevated marsh deposits and comparison with historic earthquakes constrain the date of uplift to between A.D. 1635 and 1855. Salinity changes in San Joaquin marsh suggest that uplift occurred prior to the introduction of European pollens, circa A.D. 1776–1797. Therefore, the uplift most likely occurred between A.D. 1635 and 1797. It might have been the first earthquake and aftershock sequence reported in southern California, as described by Gaspar de Portolá and his party of explorers traveling through the Orange and Los Angeles County areas in July 1769 (Grant *et al.*, 2002).

If it is assumed that an earthquake caused sudden uplift of the San Joaquin Hills, then empirical relationships between magnitude and displacement suggest a minimum magnitude between 7.1 and 7.3, depending on assumptions about the source fault (Grant *et al.*, 2002). Although there is uncertainty in the characteristics of the causative fault, the San Joaquin Hills uplift indicates recent tectonic activity equivalent to a large ($M > 7$) earthquake along the Coastal Fault Zone just prior to or at the beginning of the historic record, circa A.D. 1635–1797.

Newport-Inglewood Fault Zone

Among seismologists and the public, the most famous section of the Coastal Fault Zone is the NIFZ along the western margin of the Los Angeles basin. Based on historic seismicity and structural differences, the NIFZ is usually divided into northern and southern segments for seismic hazard assessment (Petersen *et al.*, 1994; SCECWG, 1995). Both segments have been seismically active during the historic period (Barrows, 1974). The southern NIFZ has ruptured repeatedly during the Holocene (Grant *et al.*, 1997) and generated the M_w 6.4 1933 earthquake (Hauksson and Gross, 1991) which had major historic consequences. Significant damage in the city of Long Beach and collapse of schools motivated the California legislature to enact the state's first seismic safety laws (Barrows, 1974).

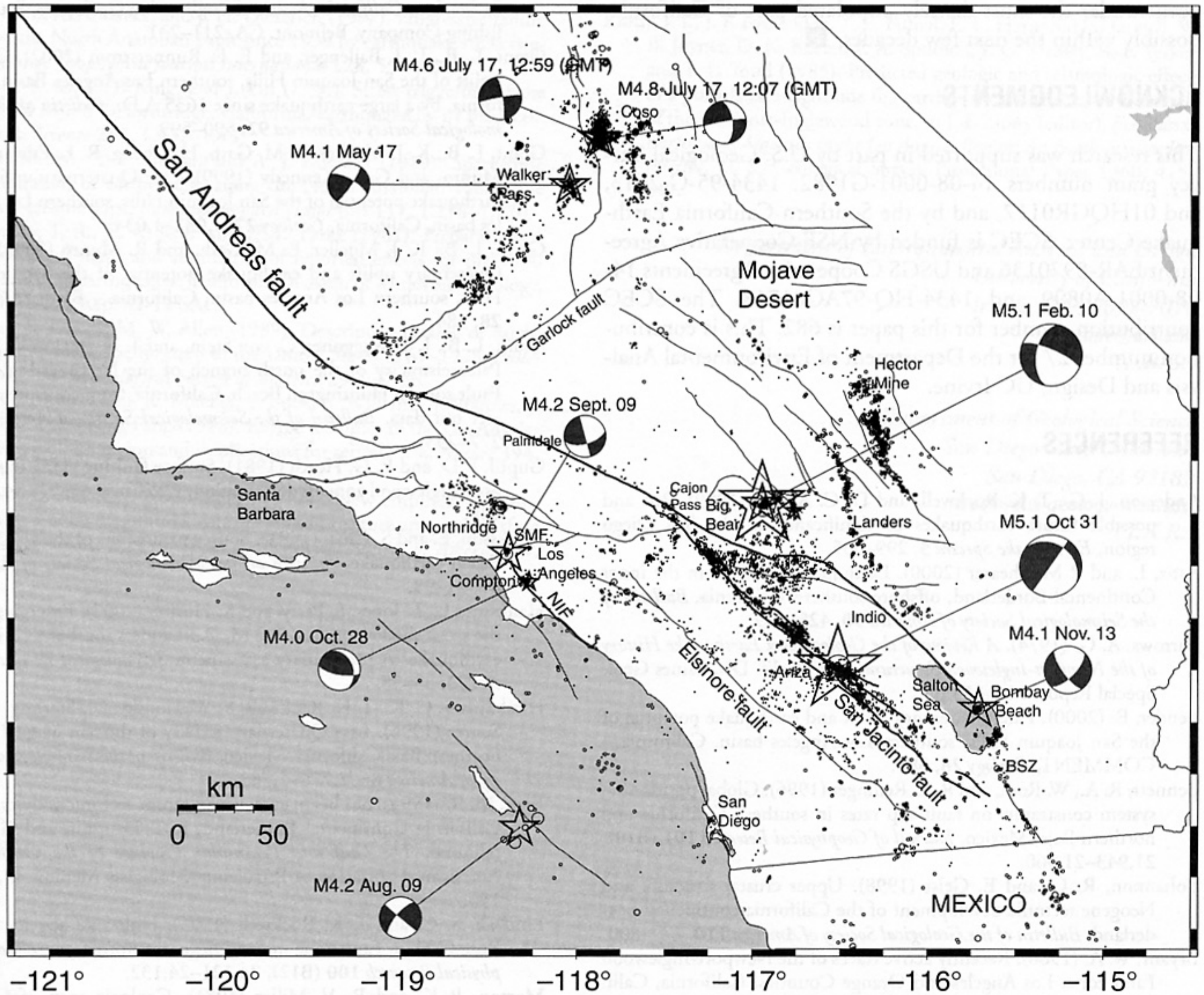
Despite relatively high historic levels of microseismicity, the northern NIFZ may be a seismic gap. The date of most recent surface rupture of the northern NIFZ is not known (Bryant, 1988). Along the southern NIFZ, paleoseismic studies suggest the most recent large surface rupture occurred several thousand years ago (Grant *et al.*, 1997). Minor surface rupture along the southern NIFZ has been attributed to the 1933 earthquake (Guptil and Heath, 1981), but evidence is equivocal (Freeman *et al.*, 1992) in part because ground failures occurred in coastal areas with soft sediments (Barrows, 1974). In sum, the paleoseismic data and historic observations suggest that the northern NIFZ has not ruptured as recently as other sections of the Coastal Fault Zone.

The California Division of Mines and Geology (1988) and U.S. Geological Survey (Ziony *et al.*, 1985) have previously identified the northern NIFZ as representing a significant seismic risk because it traverses a densely populated urban area with major cultural resources. Two moderate magnitude earthquakes along the northern segment of the NIFZ in 2001 were widely felt across the Los Angeles basin (Figure 5). A shallow (6 km depth) M_L 4.2 earthquake with a strike-slip mechanism occurred on 9 September 2001 near Beverly Hills at the northern end of the segment, following a northwest-trending cluster of earthquakes near the intersection of the NIFZ and the Hollywood Fault (Hauksson *et al.*, 2002). On 28 October 2001 a M_L 4.0 earthquake occurred at a depth of 17 to 19 km near Compton in the middle of the northern segment. Although the mechanism indicates movement on a thrust fault, an unusually energetic aftershock sequence defined a steep southwest-dipping plane that might be a restraining bend in the northern NIFZ (Hauksson *et al.*, 2002). The recent seismicity suggest that the northern NIFZ might be in the latter stages of its seismic cycle.

DISCUSSION

Within the uncertainty of dating, earthquakes on the Coastal Fault Zone can be considered a temporal cluster or rupture sequence spanning decades to centuries. The A.D. 1640 ± 160 date of the most recent rupture of the Agua Blanca Fault is indistinguishable from the A.D. 1650 ± 125 rupture date of the Rose Canyon Fault in the San Diego region. The amount of displacement (3 m) at Rose Creek suggests that the most recent rupture was a large magnitude earthquake (M ~7). The Rose Canyon rupture could have been the northern part of a longer rupture that included the Agua Blanca Fault, or the ruptures could have occurred sequentially. Uplift of the San Joaquin Hills between A.D. 1635 and 1855 (most likely before A.D. 1797) could also have occurred concurrently or sequentially with ruptures of the Rose Canyon and Agua Blanca Faults. A $M \geq 6.5$ coastal earthquake on 22 November 1800 could have occurred a few decades or a century thereafter, which was in turn followed to the north by the 1933 Long Beach earthquake on the southern Newport-Inglewood Fault.

Other observations are consistent with a model of temporally clustered ruptures along the Coastal Fault Zone. GPS measurements in Baja California reveal deformation across the San Miguel Fault, Agua Blanca Fault, and offshore faults in the "Baja California shear zone" (Bennett *et al.*, 1996; Dixon *et al.*, 2000). Total strain across the Agua Blanca and San Miguel Fault zones is approximately the same as the total geologic slip rates. However, the late Quaternary slip rate of the Agua Blanca Fault is much greater (5–6 mm/yr) than the San Miguel Fault (0.2–0.3 mm/yr) (Rockwell *et al.*, 1993; Hirabayashi *et al.*, 1996). In the last century, the San Miguel Fault has experienced seven or eight M ~6 earthquakes, while the Agua Blanca has generated only minor microseismicity (Andersen *et al.*, 1989; Hirabayashi *et al.*, 1996). These observations suggest that deformation rates have changed in the last millennium such that the San Miguel Fault zone is currently deforming faster than its long-term rate, while the Agua Blanca is deforming more slowly.



▲ **Figure 5.** Hauksson *et al.* (2002) propose that recent seismicity in southern California, including *M* 4 and *M* 4.2 earthquakes along the northern Newport-Inglewood Fault zone in 2001, suggests that the region is emerging from a stress shadow caused by the 1992 M_w 7.3 Landers earthquake. (From Hauksson *et al.*, 2002.)

If this interpretation is correct, it may reflect transient deformation associated with a multicentury- or millennial-scale rupture cycle along the entire Coastal Fault Zone, from the Agua Blanca northward, possibly in a northward-propagating sequence. If the Agua Blanca Fault failed in a large magnitude earthquake after A.D. 1640 ± 160 (or just before the historic record began), it may have triggered seismicity on the San Miguel-Vallecitos Fault, which has been much more active in historic times despite its lower slip rate.

The historic and paleoseismic records indicate that the entire Coastal Fault Zone has ruptured from the Agua Blanca to the southern NIFZ within the last few centuries, with the possible exception of the northern NIFZ and portions of the offshore NIFZ. Therefore, the densely populated northern NIFZ may be a seismic gap approaching failure. Following the 1933 earthquake, aftershocks were nearly absent along the offshore NIFZ and in the San Joaquin Hills (Hauksson and Gross, 1991), possibly due to prior strain release in the San Joaquin Hills earthquake (Grant *et al.*, 2002). In contrast, the northern NIFZ has been seismically active throughout the historic period (Barrows, 1974), with recent moderate magnitude earthquakes. The 1933 earthquake increased the failure potential of the northern NIFZ by increasing the Coulomb stress (Stein *et al.*, 1994). Occurrence of the 1994 Northridge earthquake has been attributed to a similar but smaller increase in the magnitude of Coulomb failure stress caused by the 1933 earthquake (Stein *et al.*, 1994). A similar propagating sequence of earthquakes along the North Anatolian Fault zone, Turkey may have been triggered by changes in Coulomb failure stress (Stein *et al.*, 1997). The southern California coastal fault zone might be in the later stages of an analogous, multicentury failure sequence. If so, the next earthquake in this sequence might occur under the most densely populated part of California, possibly within the next few decades.

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