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Activity of the Offshore Newport–Inglewood Rose Canyon Fault Zone, Coastal Southern California, from Relocated Microseismicity

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Abstract An offshore zone of faulting approximately 10 km from the southern California coast connects the seismically active strike-slip Newport–Inglewood fault zone in the Los Angeles metropolitan region with the active Rose Canyon fault zone in the San Diego area. Relatively little seismicity has been recorded along the offshore Newport–Inglewood Rose Canyon fault zone, although it has long been suspected of being seismogenic. Active low-angle thrust faults and Quaternary folds have been imaged by seismic reflection profiling along the offshore fault zone, raising the question of whether a through-going, active strike-slip fault zone exists. We applied a waveform cross-correlation algorithm to identify clusters of microseismicity consisting of similar events. Analysis of two clusters along the offshore fault zone shows that they are associated with nearly vertical, north-northwest-striking faults, consistent with an offshore extension of the Newport–Inglewood and Rose Canyon strike-slip fault zones. *P*-wave polarities from a 1981 event cluster are consistent with a right-lateral strike-slip focal mechanism solution.

Introduction

The Newport–Inglewood fault zone (NIFZ) was first identified as a significant threat to southern California residents in 1933 when it generated the M 6.3 Long Beach earthquake, killing 115 people and providing motivation for passage of the first seismic safety legislation in the United States (Barrows, 1974; Hauksson and Gross, 1991; Yeats, 2001). The Rose Canyon fault (RCF) zone in the San Diego area has ruptured several times during the Holocene (Lindvall and Rockwell, 1995) and poses significant seismic hazard to San Diego area residents (Anderson *et al.*, 1989). An offshore zone of faulting approximately 10 km from the southern California coast connects the strike-slip NIFZ in the Los Angeles metropolitan region with the strike-slip RCF zone in the San Diego area. The activity and seismic potential of the intervening offshore fault zone, herein referred to as the offshore Newport–Inglewood Rose Canyon (ONI-RC) fault zone, has been the subject of debate for decades (e.g., Hill, 1971; Barrows, 1974; Fischer and Mills, 1991; Rivero *et al.*, 2000; Grant and Rockwell, 2002). Recent attention has focused on blind thrusts that may intersect the ONI-RC fault zone and accommodate some of the regional deformation (Grant *et al.*, 1999; Rivero *et al.*, 2000). Interaction with the thrust system could limit the magnitude of earthquakes on strike-slip faults in the ONI-RC fault zone, if they are active. Sparse offshore microseismicity has been difficult to locate accurately (Astiz and Shearer, 2000) but has been interpreted to be associated with an active ONI-RC fault zone (Fischer and Mills, 1991). We identified, relocated, and analyzed two clusters of microearthquakes within the northern and central ONI-RC fault zone to examine the fault structure, minimum depth of seismic activity, and source fault mechanism. The results suggest that the ONI-RC fault zone is a steeply dipping, active strike-slip fault to seismogenic depths.

Tectonic and Geologic Setting

In southern California, tectonic deformation between the Pacific and North American plates is accommodated primarily by a zone of strike-slip faults (Walls *et al.*, 1998) with maximum deformation along the San Andreas system, decreasing westward into the offshore inner Continental Borderland region (Fig. 1). The inner Continental Borderland has complex structure including low-angle detachment faults, thrust faults, and high-angle strike-slip faults resulting from late Cenozoic rifting prior to the current transpressional tectonic regime (Crouch and Suppe, 1993; Bohannon and Geist, 1998). The geometry and slip rate of faults in the inner Continental Borderland are poorly constrained relative to onshore faults (Astiz and Shearer, 2000), yet they may pose significant seismic risk because they are close to populated areas, and several offshore faults appear to displace seafloor sediments (Legg, 1991). Grant and Rockwell (2002) proposed that an active >300-km-long Coastal Fault zone (Fig. 2) extends between the Los Angeles basin (USA) and coastal Baja California (Mexico), including the NIFZ and RCF zone in southern California, the Agua Blanca fault in

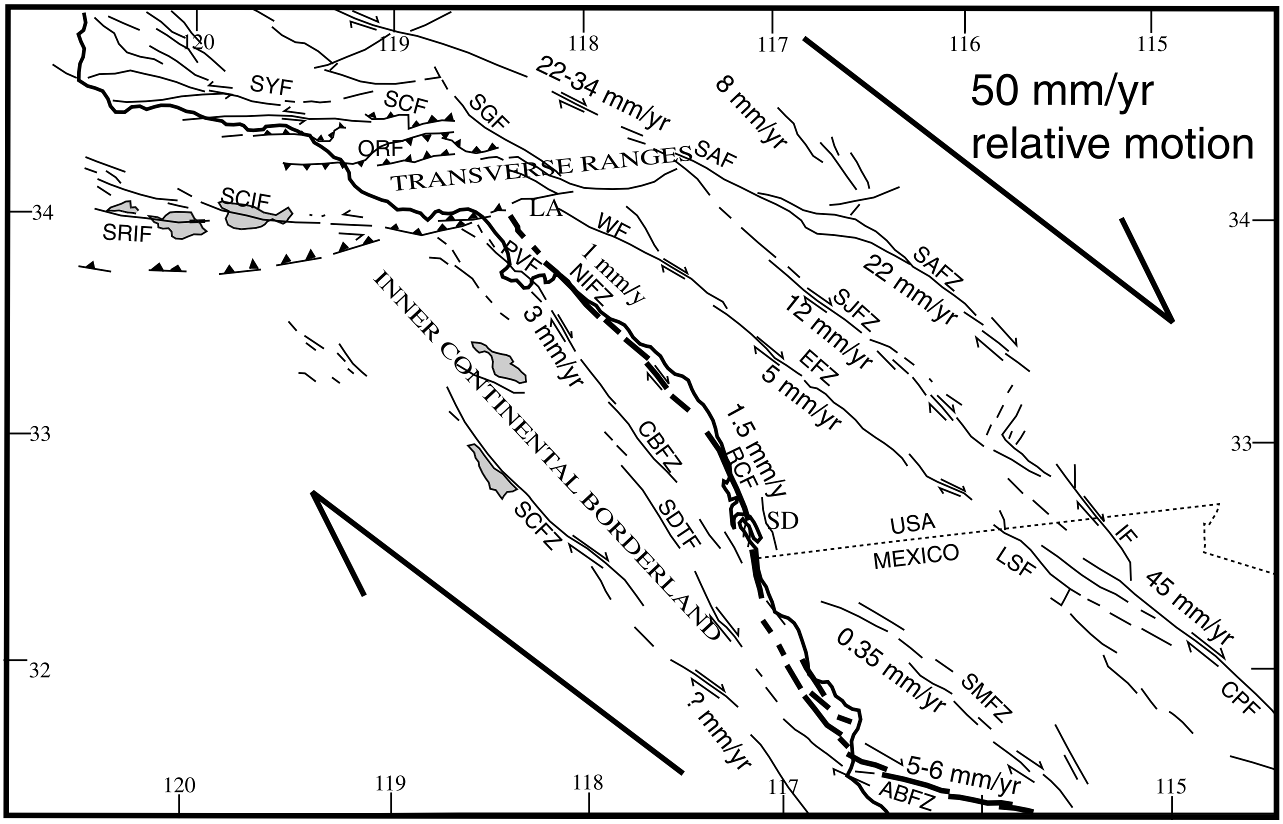

Figure 1. Regional fault map (modified from Grant and Rockwell [2002]; after Walls *et al.* [1998]) summarizing regional tectonic deformation according to slip rate on major faults, including the San Andreas fault (SAF), San Jacinto fault zone (SJFZ), Elsinore fault zone (EFZ), Whittier fault (WF), Palos Verdes fault (PVF), NIFZ near Los Angeles (LA), RCF zone (RCFZ) near San Diego (SD), Agua Blanca fault zone (ABFZ), San Miguel fault zone (SMFZ), Imperial fault (IF), Cerro Prieto fault (CPF), and Laguna Salada fault (LSF). Offshore faults of the inner Continental Borderland include the Coronado Bank fault zone (CBF), San Diego Trough fault (SDTF), San Clemente fault zone (SCFZ), Santa Cruz Island fault (SCIF), and Santa Rosa Island fault (SRIF). The San Gabriel fault (SGF), San Cayetano fault (SCF), Oak Ridge fault (ORF), and Santa Ynez fault (SYF) are located in the Transverse Ranges.

Baja California, and contiguous offshore fault zones. The structural style and slip rates of the NIFZ and RCF zone suggest that the intervening ONI-RC fault zone is an active, strike-slip fault zone with complex structure and a slip rate of 0.5–2.0 mm/yr.

The NIFZ has been studied extensively in the Los Angeles basin by petroleum geologists. Hill (1971) proposed that the NIFZ overlies a major tectonic boundary separating eastern continental basement facies of granitic and associated metamorphic rocks from oceanic Catalina schist facies of the inner Continental Borderland province to the west. The current strike-slip faulting regime apparently reactivated a structural weakness along the Mesozoic subduction zone (Hill, 1971) and initiated right-lateral motion in the mid-to-late Pliocene (Wright, 1991; Freeman *et al.*, 1992). The NIFZ is a structurally complex series of discontinuous strike-slip faults with associated folds and shorter normal and reverse faults (Yeats, 1973), described by Wilcox *et al.* (1973) and Harding (1973) in a set of classic papers on wrench tectonics. Dextral displacement of late Miocene and younger sediments reveals a long-term slip rate of 0.5 mm/yr (Freeman *et al.*, 1992). Multiple surface ruptures since the early Holocene indicate that the minimum slip rate is at least 0.3–0.6 mm/yr and may be substantially higher (Grant *et al.*, 1997). A Holocene slip rate of ~1 mm/yr has been assumed for seismic hazard assessment (SCECWG, 1995). Seismically active strands of the NIFZ have been mapped along the western margin of the Los Angeles basin between the cities of Beverly Hills and Newport Beach (Bryant, 1988; Grant *et al.*, 1997) where the fault steps over and continues offshore parallel to the coast (Morton and Miller, 1981).

The subsurface structure and tectonic history of the RCF zone have not been studied as thoroughly as the NIFZ because it lacks petroleum reserves. The Holocene sense of movement and slip rate of the RCF have been investigated for seismic hazard studies. Lindvall and Rockwell (1995)

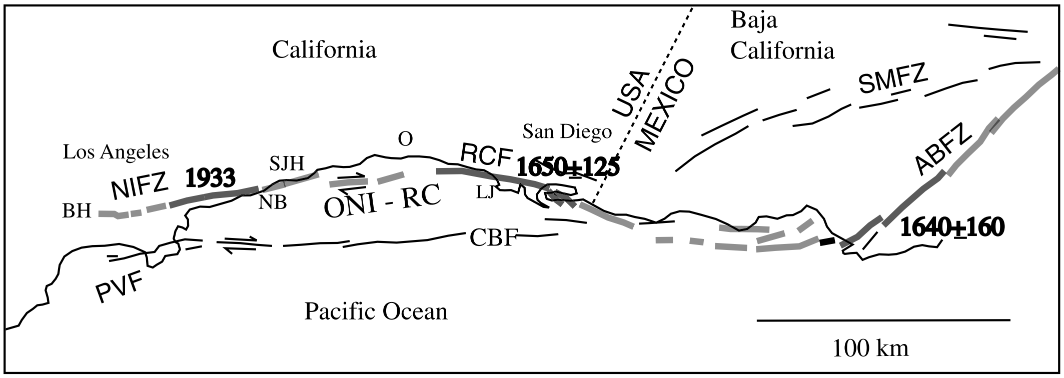

Figure 2. Map shows approximate location of major strands in the Coastal fault zone and dates of most recent rupture. The Coastal fault zone includes the northern NIFZ near Beverly Hills (BH) (dashed), southern NIFZ (bold) near Newport Beach (NB), the ONI-RC fault zone (gray) offshore of the San Joaquin Hills (SJH) and city of Oceanside (O), the RCF zone (bold line) between La Jolla (LJ) and San Diego, the Coronado Bank fault zone (CBF), and the Agua Blanca fault zone (ABFZ, bold). Modified from Grant and Rockwell (2002); after Grant *et al.* (1997), Lindvall and Rockwell (1995), and Rockwell and Murbach (1999).

and Rockwell and Murbach (1999) reported that it is primarily a strike-slip fault zone with a slip rate of 1–2 mm/yr, although individual strands display varying amounts of dip-slip motion in combination with strike slip.

Location and Structural Models of the ONI-RC Fault Zone

The location of the ONI-RC fault zone has been mapped by seismic reflection profiling in shallow water along the inner continental margin between Newport Beach and La Jolla, north of San Diego. Fischer and Mills (1991) summarized the results of eight investigations between 1972 and 1988, including unpublished mapping for the nuclear generating station at San Onofre. Interpretations of Fischer and Mills (1991) and prior studies disagree about the location and number of traces, but all reveal a fairly continuous zone of faulting within a few kilometers of the coastline. Fischer and Mills (1991) presented several interpretive cross sections with a steeply dipping fault and flower structure suggestive of strike-slip motion. They described an inner and outer "thrust fault-fold complex" consisting of multiple thrust faults and thrust-generated folds associated with a positive flower structure, and they described an offshore extension of the San Joaquin Hills as being dextrally offset by the ONI-RC fault zone. Grant and others (1999, 2000, 2002) reported late Quaternary and Holocene uplift of the San Joaquin Hills inboard of the ONI-RC fault zone and suggested that seismic activity of the San Joaquin Hills blind thrust and ONI-RC fault zone are linked.

Recent offshore investigations have focused on the structure and potential activity of a low-angle fault, the Oceanside thrust, and its relationship to the ONI-RC fault zone (Bohannon and Geist, 1998; Rivero *et al.*, 2000). Rivero *et al.* (2000) proposed that the San Joaquin Hills blind thrust is a backthrust soling into the larger Oceanside thrust. In this model, Quaternary uplift of the San Joaquin Hills and coastline south to San Diego is associated with movement of the Oceanside thrust. They presented four potential configurations for thrust interaction with strike-slip faults in the ONI-RC fault zone, each leading to a different maximum magnitude estimate, based on the activity and depth of the strike-slip system. Our analysis of microseismicity helps constrain the most viable model for interaction between the Oceanside thrust and ONI-RC fault zone.

Seismicity and Event Location Method

No significant historic earthquakes have occurred on the ONI-RC fault zone. Scattered seismicity has been recorded along the ONI-RC fault zone (Fig. 3), although events are difficult to locate accurately due to poor station coverage (Fischer and Mills, 1991; Astiz and Shearer, 2000). With the exception of the energetic 1986 M_L 5.3 Oceanside earthquake sequence, rates of microseismicity have been low since digital waveform data became available in 1981 (Astiz and Shearer, 2000). Fischer and Mills (1991) reported that the rate of seismicity along the ONI-RC fault zone is approximately 10 times lower than along the onshore NIFZ. Rivero *et al.* (2000) interpreted the 1986 Oceanside earthquake sequence as generated by the Thirtymile Bank thrust fault, a reactivated low-angle detachment fault.

Figure 3 shows microseismicity of the inner Continental Borderland between 1981 and February 2003. The earthquake locations were computed from the archived *P* and *S* picks using the source-specific station term method of Richards-Dinger and Shearer (2000). This method improves the relative location of events within compact clusters by solving for custom station terms for subsets of the events, thus removing the biasing effects of unmodeled three-

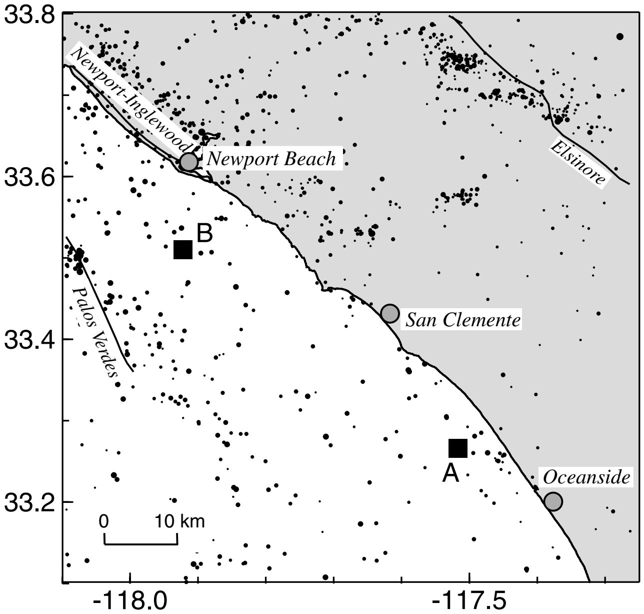

Figure 3. Earthquakes (black dots) near the coastal cities (circles) of Newport Beach, San Clemente, and Oceanside, California, recorded from 1981 to February 2003. Black boxes indicate clusters of similar events near the ONI-RC fault zone. A 1981 cluster near Oceanside (box A) is shown in Figure 4, and a 2000 cluster near Newport Beach (box B) is shown in Figure 5. The approximate locations of the Elsinore, Newport–Inglewood, and Palos Verdes faults are also shown.

dimensional velocity and the varying station coverage among the events. In general, this results in sharper and better-defined seismicity alignments. The method does not, however, necessarily yield improvements in the absolute locations of the clusters. We obtained waveforms for these events and performed waveform cross-correlation between each event and 100 neighboring events (Shearer, 1997; Astiz *et al.*, 2000). We then identified clusters of similar events and relocated the microearthquakes within similar event clusters using the method of Shearer (1998, 2002). On Figure 3, each cluster is so compact that these appear mostly as single dots. Two of these clusters, in boxes labeled A and B in Figure 3, are associated with the ONI-RC fault zone and are the focus of this article.

Results

The Oceanside Cluster

The most interesting cluster is from a 1981 swarm of 19 $M < 3.0$ earthquakes approximately 10 km northwest of Oceanside. This cluster should not be confused with the more energetic 1986 M_L 5.3 Oceanside earthquake sequence located much further offshore. As shown in Figure 4, the events align along a north-northwest trend about 0.5 km long. In cross section, the events define a nearly vertical plane between 12.5 and 13.0 km depth. The strike, dip, and

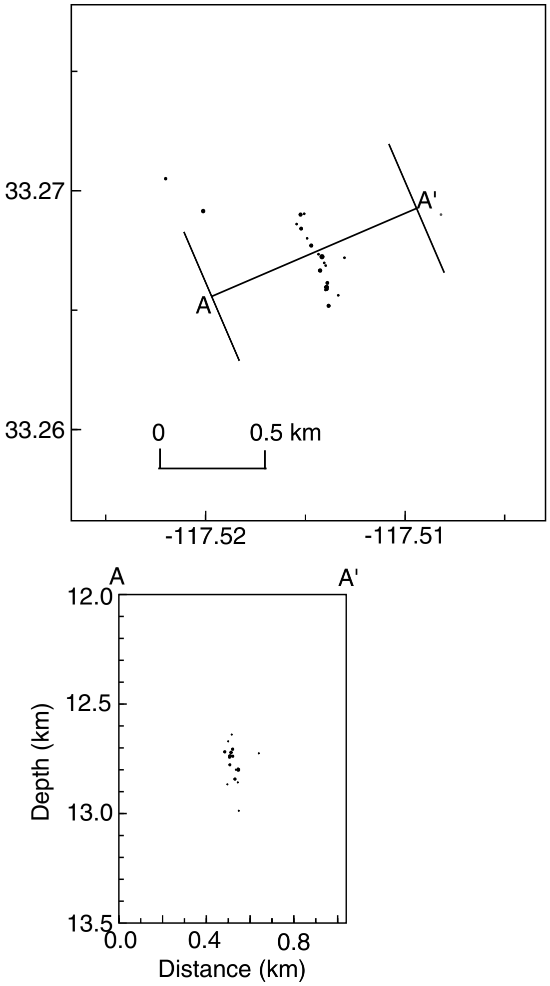

Figure 4. The 1981 Oceanside cluster (from box A on Fig. 3) is plotted at higher resolution in map view and cross section, after relocation using differential times computed using waveform cross-correlation.

location of a plane fit by these events are consistent with active strike-slip faulting on the ONI-RC fault zone.

Fischer and Mills (1991) reported that the 1981 cluster represents “a direct correlation of seismicity” (p. 30) with the ONI-RC fault zone because they located the earthquakes within 0.5 km of where they mapped the Oceanside segment of the fault zone. Our relocation results support this interpretation by showing that the events within the cluster form a linear trend that is approximately parallel to the fault zone. Fischer and Mills (1991) also calculated a strike-slip single event first motion focal mechanism solution for an earthquake in the 1981 cluster. We are doubtful that unique focal mechanisms can be computed for the 1981 events, given the sparse distribution of seismic stations. However, we did examine composite waveform polarities from the 1981 cluster using the method of Shearer *et al.* (2003) and found that the polarities are consistent with a right-lateral strike-slip focal mechanism solution, aligned with the trend of the ONI-RC fault zone. We cannot, however, entirely eliminate other possible focal mechanisms.

The Newport Beach Cluster

A cluster of seven similar microearthquakes occurred offshore of Newport Beach in 2000 at a depth of approximately 6.5–7.0 km. The cluster is near the offshore NIFZ as mapped by Morton and Miller (1981) and compiled by Fischer and Mills (1991). In map view and cross section (Fig. 5), five of the seven events are aligned in a pattern consistent with a shallow (7 km), north-northwest-striking, vertical or steeply dipping active fault. Observed polarities for this cluster are too sparse to provide any meaningful constraint on the focal mechanisms.

The location of the 2000 cluster is southwest of an area of active faulting reported by Fischer and Mills (1991) from mapping offshore of Newport Beach and the San Joaquin Hills. Fischer and Mills (1991) analyzed microseismicity from 1982 to 1990 along this zone and reported strike-slip and reverse-fault first motion solutions from a cluster of epicenters between 2 and 2.5 km on either side of the mapped fault zone.

Discussion

The mean locations of each cluster are determined using a standard 1D velocity model for all of southern California and are probably not very accurate, particularly in depth. We estimate uncertainties on the absolute cluster locations as roughly ± 2 km in horizontal position and ± 5 km in depth. However, the relative location accuracy among events within each cluster is much better constrained, so the trends defined by the seismicity alignments should be reliable. The estimated relative location accuracy is generally less than 50 m for the events in the Oceanside cluster and less than 150 m for the aligned events in the Newport Beach cluster. The two outlying events in the Newport Beach cluster have standard errors of about 500 m; thus it is entirely possible that their true locations lie within the linear trend of the other events.

The location, alignment, and apparent dip of the Oceanside and Newport Beach clusters of microearthquakes are consistent with the presence of active, steeply dipping faults in the ONI-RC fault zone. Waveform polarities are also consistent with strike-slip motion, although other mechanisms cannot be ruled out.

For hazard estimation of offshore faults, it is not as important to precisely locate active traces as it is for onshore faults in populated areas. A more important consideration is the potential for a through-going rupture and an estimate of the maximum magnitude earthquake. Our relocated microseismicity is too sparse to reveal whether or not there is a through-going strike-slip fault zone. The structure of the ONI-RC fault zone may be similar to that of the onshore NIFZ, which contains multiple strike-slip traces. Others have mapped a fairly continuous structurally complex zone of faulting ~110 km long, subparallel to and within 10 km of the coast (Fischer and Mills, 1991). The maximum magnitude of an ONI-RC fault rupture can be estimated from the length of the fault zone. Assuming a 110-km surface rupture length of a strike-slip fault zone yields an estimated *M* 7.4 earthquake (Wells and Coppersmith, 1994).

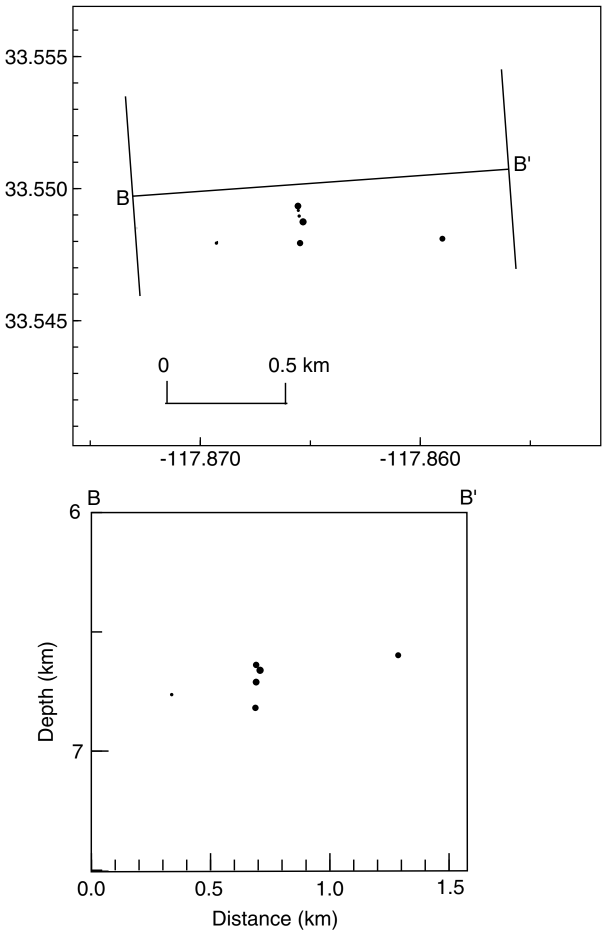

Figure 5. The 2000 Newport Beach cluster (from box B on Fig. 3) is plotted at higher resolution in map view and cross section, after relocation using differential times computed using waveform cross-correlation.

If strike-slip faults do not terminate the Oceanside thrust, Rivero *et al.* (2000) estimate an M_w 7.5 maximum magnitude earthquake could result from rupture of the entire thrust fault. The ~6.5-km depth of the Newport Beach seismicity cluster does not provide information on the geometry or interaction between the strike-slip ONI-RC fault zone and the Oceanside thrust. However, the location and ~13 km depth of the Oceanside cluster suggests that the Oceanside thrust is terminated by active strike-slip faults. According to Rivero *et al.* (2000), this geometry would lead to an M_w 7.3 maximum magnitude earthquake on the Oceanside thrust. The maximum magnitude estimate is at the upper range of magnitude estimated for an earthquake that uplifted the San Joaquin Hills circa A.D. 1635–1769 (Grant *et al.*, 2002).

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