

Earthquake Potential of Major Faults Offshore Southern California

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Major active faults offshore southern California pose a serious threat to coastal populations and structures. These faults are modestly well known, though they are often not considered in tectonic models and seismic hazard assessments because their Holocene activity and slip rates are unknown. For example, the seismic hazard mapping prepared by the USGS and CDMG omitted two of the largest and most continuous offshore faults--San Clemente Fault and San Diego Trough Fault due lack of data on recency of motion and slip rate. Yet because of the great length of these structures, exceeding 300-500 km, and well-defined character of these faults, they have the potential to generate large magnitude ($M > 6.5$) earthquakes that would be destructive to heavily populated coastal areas including San Diego, Los Angeles, and Orange Counties. Indeed, these faults are closer to the southern California coast than the severely damaged Marina district and collapsed Cypress freeway are to the 1989 Loma Prieta rupture area. Long-period shaking effects due to large offshore earthquakes may be equally destructive to vulnerable coastal structures of southern California.

We have compiled a comprehensive bathymetric dataset including recent high-resolution multibeam (SeaBeam and Simrad) bathymetry and NOAA hydrographic data offshore southern California and northern Baja California. These data cover the major portions of the two largest faults within the inner borderland offshore southern California: the San Clemente and the San Diego Trough fault zones, as well as parts of the Palos Verdes-Coronado Bank Fault. These data provide an accurate delineation of fault geometry and character, and illuminate numerous piercing point offsets on a variety of scales. Combined with a dense grid of existing high-resolution single-channel seismic reflection data and observations from the submersible ALVIN, these data are sufficiently detailed to allow a first-order estimate of rates of deformation. These data will allow generation of new detailed maps of these faults that will, for the first time allow an accurate assessment of fault segmentation and the relationship of fault morphology to seismicity.

Recent observations from the DSV Alvin provide the first confirmation of large prehistoric earthquake occurrences on the submarine San Clemente fault, and allow more accurate interpretation of submarine fault earthquake potential than previously possible. The detailed fault mapping will allow delineation of the lateral extent of major fault segments that will be used to estimate the rupture characteristics; the Alvin observations of fault scarp heights will be used to estimate characteristic fault displacements for large earthquakes. Recognition of offset piercing points from the combined seafloor geomorphology and subsurface imaging will allow estimation of the, heretofore elusive submarine fault slip rates. Seafloor displacement during large submarine earthquakes represents the added potential for generation of destructive local tsunamis.

Direct hazards from earthquakes and earthquake generated tsunami offshore may not be the only, or even the largest hazard to coastal southern California. As our experience from the 1946 Aleutian event, and more recently from Papua New Guinea, a modest earthquake may generate a large submarine slide and associated tsunami that is out of proportion to the earthquake magnitude. Such scenarios are plausible for southern California, where earthquake sources are numerous, and the borderland topographic highs are ringed by submarine slides that are now being revealed by new multibeam mapping.

Ancient Shorelines and Active Tectonics

The study of continental margin tectonics involves the use of geodetic data, including trilateration, levelling, and GPS data in order to reveal short-term vertical and horizontal motions of the Earth's crust. Marine terrace data can reveal a longer term permanent deformation pattern (Berryman, 1993; Berryman et al., 1997; Kelsey et al., 1992; 1994; McCrory, 1996; Thatcher, 1994). But these lines of investigation end at the coastline, and information about vertical tectonics in the submarine environment is elusive, and mostly limited to low-resolution micropaleontological studies of the preferred depths of benthic fauna. Onshore, marine terraces are evidence of sea-level still stands during Pleistocene glacial minima, and record deformation over longer geologic intervals. Offshore, similar evidence exists along many of the world's continental shelves in the form of low-stand shorelines cut during glacial maxima. Recently, sidescan sonar, swath bathymetry, high-resolution seismic reflection profiling, and submersible observations have allowed the mapping of submerged lowstand shorelines, as well as deformed stream channels and other deformed features, leading to the determination of deformation mechanisms and rates.

Shorelines Around Southern California's Channel Islands

Along the northern edge of the borderland lies the west-trending, Western Transverse Ranges (WTR) structural block. Miocene breakup and rifting of the WTR block away from the Peninsular Ranges, exhumed the Catalina Schist basement rocks within the widening gap now recognized as the Inner Borderland Rift (IBR; Legg, 1991; Crouch and Suppe, 1993). Today, clockwise rotation of the elongate WTR block continues during the late Cenozoic right-lateral shear of North America (Kamerling and Luyendyk, 1979; Luyendyk and others, 1980). At the northern boundary, where the northwest structural fabric of the IBR impacts the WTR, a major fold-and-thrust belt has developed and vertical tectonism is dominant. The Transverse Ranges have rotated 90° clockwise since the late Miocene (Kamerling and Luyendyk, 1979; Luyendyk, et al., 1980). The present orientation of structures in the Transverse Ranges today is nearly normal to the dominant NNE tectonic compression (Mount and Suppe, 1992). The same stress orientation would be expected to drive the NW-trending faults of the Peninsular Ranges and California continental borderland in a right-lateral sense. One of the most interesting tectonic problems is what happens when the strike-slip peninsular range faults intersect the thrust faults of the Transverse ranges. These faults must either "subduct" along with some portion of the inner and outer Borderlands blocks, or they must accommodate rotation of the Transverse Ranges, with local deformation at their intersection with the thrust front.

In recent NOAA/NURP funded project to address these issues, we collected sidescan sonar, sub-bottom reflection profiles, and submersible observations of these faults and the submerged shorelines around them to use the shoreline data as a tectonic indicator.

Our recent work includes shorelines in Santa Monica Bay, the Palos Verdes Peninsula, off Santa Cruz and Anacapa Islands, and along the mostly submerged Catalina Ridge. Each of these localities has a well-defined shoreline and beach defining the last glacial maximum, and each of them is presently at a different elevation, reflecting post-20 Ka tectonics. Recent DELTA dives off Santa Cruz and Anacapa Islands located the Last Glacial Maximum (LGM) lowstand along the southern margin along the shelf at a present depth of 100 m. The Channel Islands shorelines are distinctive and are marked by obvious shell hash beaches, shoreface sands (with ripple marks intact), and seacliffs. At Pilgrim Bank, and an unnamed(?) bank on the northern end of the submerged Catalina Ridge we also observed well developed shorelines with sea stacks, wave-cut

sea caves, shell hash and pebble beaches, and preserved ripple marks. We collected numerous *Mytilus* and barnacle shells from rich Pleistocene fauna we found the Channel Islands shorelines for future dating.

Our new reflection data suggest that right slip of the Peninsular Range faults is accommodated by minor "subduction" of the western block of each pair, though this requires further analysis. We used deformation of the shorelines to examine some of the post-20 ka deformation. The 100 m elevation of the shoreline along the Santa Cruz Island Fault indicates 20-35 m of uplift of the islands, at a rate of ~ 1-1.8 mm/yr, while the shoreline on the adjacent Catalina Ridge was found at a depth of 110-115 m, indicating uplift at a much lower rate of 0.5-1.3 mm/yr. The differential rate may indicate relative motion of the lower plate block downward along the thrust fault at the leading edge of the Transverse Range Block. Seismic reflection data suggest other lower shorelines along the top of the Catalina Ridge, suggesting at least one prior period of subsidence.

Understanding the tectonics and also the associated earthquake and tsunami hazards of the Borderland will require a variety of approaches. One key avenue will be to acquire multibeam bathymetry for much of the unsurveyed Borderland region. Borderland regional tectonics are presently poorly known despite the relative abundance of reflection seismic data. One reason is that the recent tectonics are dominated by strike-slip, and thus are difficult to resolve with reflection profiling, but made much simpler with detailed bathymetry from which piercing point offsets and slip histories can be reconstructed. Bathymetry will also allow examination of the low-stand shorelines, which in turn reveal the vertical tectonics of the last 20ka, as well as longer time scales with high resolution. The vertical tectonic history can in turn reveal such important tectonic details such as the behavior of restraining bends, and the slip rate of the frontal Transverse Range thrust