U.S.Geological Survey Grant No. **01HQGR0018**

EARTHQUAKE POTENTIAL OF MAJOR FAULTS OFFSHORE SOUTHERN CALIFORNIA: COLLABORATIVE RESEARCH WITH OREGON STATE UNIVERSITY AND LEGG GEOPHYSICAL

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February 2002

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Program Elements:
I-Products for Earthquake Loss Reduction; **II**-Research on Earthquake Occurrence and Effects
Key Words: Neotectonics, Seismotectonics, Tectonic Geomorphology, Tectonic Structures

Abstract

Major active faults offshore southern California are poorly known with respect to slip-rates and seismic hazards. However, due to their long strike length, apparent recencey of motion based on new multibeam bathymetry and submersible observations, these faults may pose a serious threat to coastal populations and structures. Due to the relative paucity of hazard data, they are often not considered in tectonic models and seismic hazard assessments. . For example, the seismic hazard mapping prepared by the USGS and CDMG omitted two of the largest and most continuous offshore faults, the 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. Critical port facilities such as those at Long Beach and San Pedro would be easily disrupted by even modest ground movement of the fill they are constructed on.

We have compiled a comprehensive bathymetric dataset including recent high-resolution multibeam (SeaBeam 2000 and 2100 and Simrad (EM 120 and EM 1000) bathymetry Scripps underway multibeam data back to the early 1980’s, and dense NOAA hydrographic sounding offshore southern California and northern Baja California. These data cover the entire Borderland, including 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 zone. These data provide an accurate delineation of fault geometry and character, illuminate numerous piercing point offsets on a variety of scales, and provide at least qualitative geomorphic evidence of recency of movement and rate of slip 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. In this first year study, we generated new detailed maps of the San Clemente fault zone, and part of the San Diego Trough fault zone, that allows 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 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 allows delineation of the lateral extent of major fault segments that are used to estimate the rupture potential; the Alvin observations of

fault scarp heights are used to estimate fault displacements for large earthquakes. Preliminary recognition of offset piercing points from the combined seafloor geomorphology and subsurface imaging allowed estimation of the, heretofore elusive submarine fault slip rates for part of the San Clemente fault zone. Seafloor displacement during large submarine earthquakes represent the added potential for generation of destructive local tsunamis, which may come from either fault motion itself, or triggered submarine landslides. Preliminary models from this project suggest that coastal run-up elevations would be comparable to the maximum seafloor uplift at the source. The occurrence frequency of such events remain to be estimated along with the fault uplift and lateral slip rates. Another general finding is that the perception that strike-slip faults do not generate tsunami is incorrect. Strike slip faults generate significant vertical motion at both reastraining and releasing bends. Elastic strain accumulation at either of these strucures, when released, has a large vertical component. Additionally, the horizontal movement of steep submarine topographic fearures anelastically during a strike-slip earthquake can generate a tsunami.

Results of the completed work are important for upgrading the seismic hazard models of the southern California region to more accurately assess shaking and related hazards to coastal areas. In particular, the long-period shaking effects and induced ground failure such as liquefaction or sea cliff and coastal slope failures may be assessed. Large coastal structures such as power plants, port facilities, bridges and roadways, railroads, refineries, and other important facilities are vulnerable to long-period shaking, and therefore, it is imperative to accurately assess this hazard along the coast. Similarly, efforts to assess inundation hazards from locally generated tsunamis also require accurate assessment of offshore faulting and seafloor deformation from large earthquakes.

EARTHQUAKE POTENTIAL OF MAJOR FAULTS OFFSHORE SOUTHERN CALIFORNIA

1. Investigations Undertaken

1.1 *Fault Mapping*

Prepare large-scale maps of seafloor bathymetry from SeaBeam and dense echo-sounding grids.

Location map of study, major fault zones, and regional bathymetry (Fig. 1).

Scale: 1:250,000 for regional mapping of large area; details for some sections at 1:100,000 scale including northern Baja California area (Legg, 1985); Fault mapping for Probabilistic Seismic Hazard Assessment: Scale 1:750,000 (cf., Jennings, 1994).

Accuracy and Resolution: Multibeam bathymetry navigational accuracy within 10-50 m based on P-code or differential GPS; conventional echo-sounding locations within 50 horizontally, 1 m vertically m in U.S. waters from NOAA hydrographic surveys, 100-500 m in Mexican waters (Legg, 1985); Bathymetry gridded and contoured at 20-100 grid spacing within Study Area..

Compile and interpret existing seismic reflection profiles to determine fault character, recency, dip

Map showing location of seismic reflection profiles, single-channel and MCS, (Fig. 2).

Sources: Moore, 1969; Vedder, 1975; Moore and Beyer, 1975; Kennedy et al, 1980; Legg, 1985; Bohannon et al, 1990a, b; Bohannon and Geist, 1998).

Accuracy and Resolution: Seismic trackline navigational accuracy within 100 m for special surveys, within 100-500 m generally for Study Area; 0.5 to 5.0 km for remote areas (southern borderland).

Map active fault traces using seafloor geomorphology and seismic profiles.

Map showing major fault sections of the San Clemente and San Diego Trough fault zones (Figs. 1-4).

Stratigraphy and recency of fault definitions, seismic stratigraphy and geomorphic character (Figs. 5 & 6; Vedder et al, 1974; 1986; Junger and Wagner, 1977; Clarke et al, 1987; Greene and Kennedy, 1987; Legg, 1985).

Accuracy and Resolution: Fault mapping from multibeam bathymetry (geomorphology) within 100 m (100 m grid spacing), and within 100-500 m for large-scale maps, within 500 m for Study Area fault map (Fig. 1); fault locations probably within 0.5-1.5 km for southern borderland.

Import fault maps into Geographic Information System.

Geographic meta-data for fault mapping, datum and coordinate systems (NAD-27, lat/lon coordinates, Clarke 1866 spheroid), resolution/accuracy (100-500 meters); (ascii file: brdldflt.bna).

Prepare publication-quality maps and 3-D perspective views of seafloor deformation.

Important tectonic geomorphologic structures along the fault zones (Figs. 7 & 8).

1.2 *Earthquake Potential, Magnitude and Segmentation*

Compile and interpret seismic refraction and microseismicity data for fault depth, thickness.

Sources: Shor and Raitt, 1958; Shor et al, 1976; Corbett, 1984; Astiz and Shearer, 2000.

Determine Maximum Magnitude based on fault length and area from empirical data.

Table I (Major fault segments and maximum magnitudes), Table II (California Seismic Source Parameters).

Define major fault segments, boundaries, character and "characteristic" earthquake magnitudes.

Map showing major fault sections of the San Clemente and San Diego Trough fault zones (Fig. 1).

1.3 *Slip Rates and Recurrence Interval*

Identify candidate piercing points.

Major features 55-60 km right-slip for San Clemente fault zone (Figure 5; Goldfinger et al, 2001).

32-36 km oblique extension for San Diego Trough fault zone (Legg, 1991).

Compile and interpret 3.5 kHz data for Recent (late Quaternary) deformation.

Seismic stratigraphy for Holocene, late Quaternary (Legg, 1985; Janik, 2001).

Contour isopachs and structural elevations of late Quaternary and Holocene horizons.

Not completed in Year 1; Isopachs of PEL in Bend Region (Legg et al, 1999).

Estimate stratigraphic ages based upon existing piston cores in area.

PEL from Dunbar, 1981; Smith and Normark, 1976; ODP 167, Janik, 2001.

Compare geologic with geodetic and seismicity estimates of slip rates.
Geologic (preliminary) exceeds geodetic (Bennett, et al, 1996; Larson, 1993).

1.4 *Tsunami Potential*

Identify areas and character of oblique faulting with seafloor uplift/subsidence.
Bend Region, San Clemente fault zone (Legg et al, 1999); Santa Catalina Island (in progress).
Contour isopachs and structural elevations to quantify uplift or subsidence rates.
PEL in Bend Region (Legg et al, 1999).
Elastic dislocation modeling for single-event deformation, tsunami and earthquake potential.
Model 2 meter seafloor uplift, results in 2 meter tsunami run-up elevation on adjacent coast (Figs. 9 & 10; Legg and Borrero, 2001).

2. **Results**

The primary research objective was to produce more accurate maps of the recently-active traces of two major fault systems of the Inner California Continental Borderland (Figs. 1-4): 1) San Clemente fault system; 2) San Diego Trough fault system. The term *fault system* refers to a collection of fault zones that are inferred to be tectonically related and generally lie in close spatial proximity or form a relatively continuous zone of deformation along strike. A *fault zone* is a collection of tectonically related fault segments that are more closely aligned and interconnected than the larger scale fault system. A fault zone is inferred to represent the surface expression of a more continuous zone of tectonic shear deeper in the crust. For assessment of earthquake potential, within each fault zone are Mark can we just talk about segments, and have it be scale independent? Don't know that we need two categories. defined *fault sections*that represent a laterally continuous part of the fault zone that is separated from neighboring sections by distinct geometric or other irregularities in the trace of the principal displacement zone. Fault sections are typically several tens of kilometers in length for the major fault zones considered herein. Within the fault section are one or more *fault segments* that consist of relatively continuous fault traces at the mapped scale used. Fault segments are often considered capable of rupturing along the entire length during moderate to large earthquakes in hazards models, though the basis for this is not very robust. *Cascades* of simultaneous rupture of multiple segments within a fault section of even among multiple fault sections may occur during particularly large earthquakes like Landers in 1992.

2.1 *San Clemente Fault System* Seven major recently-active fault sections of the San Clemente fault system are recognized (Tables I & II, Fig. 1). The overall fault system, comprised of the major San Clemente and San Isidro fault zones, has a lateral extent approaching 600 km, reaching from the southeast flank of Santa Cruz Island, Santa Barbara County, California, to the continental shelf area near Punta Baja, Baja California Norte, Mexico. The northern section consists of the Santa Cruz - Catalina Ridge fault zone, and includes the northern part of the East Santa Cruz Basin fault zone. The San Clemente Island fault section comprises the north central section and consists of eight sub-sections or fault segments (Fig. 3). Spanning the international border is the Navy Basin section, which generally delineates the eastern flank of a long, narrow, pull-apart basin. To the south, the Bend Region consists of a major restraining bend with attendant seafloor uplift (Figs. 4 and 6) that connects the San Clemente fault zone with the San Isidro fault zone west of Baja California, Mexico. The northern section of the San Isidro fault zone cuts across the late Pleistocene to Holocene Shepard and Banda submarine fans west of northern Baja California, Mexico (Fig. 4). The Descanso Plain segment is transtensional, with downwarping of late Pleistocene sediments into an elongate trough (sag) aligned with the main fault traces (Fig. 5). The Ensenada Trough segment is a narrow well-defined zone that appears to be pure right-slip with little seafloor offset, except at its northern end where it displaces the Banda submarine fan about 4 km to the northwest. The segments farther to the south are beyond the scope of this project and not discussed further.

EARTHQUAKE POTENTIAL OF MAJOR FAULTS OFFSHORE SOUTHERN CALIFORNIA

Three recent cruises to the southern San Clemente fault zone in the California Continental Borderland focused on active tectonic and bio-geologic processes associated with this major offshore fault system. We combined new multibeam bathymetry data collected in 1998-2000 with existing multibeam and sounding data to produce a new bathymetric grid for the Borderland in the U.S.-Mexico border region. The new grid reveals both broad and fine scale tectonic geomorphic relationships along the San Clemente, San Diego Trough and other fault systems (Figs. 7 & 8). The dominant dextral nature of the Borderland faults is revealed by offset drainages, offset basement highs, and the numerous restraining and releasing bends and fault offsets that control the vertical tectonics on both fine and regional scales. For example, well imaged bathymetric piercing point offsets demonstrate that San Clemente Island itself is offset right laterally about 60 km from the submerged Fortymile Bank to the east (Fig. 7) as originally proposed by Shepard and Emery (1941). On a smaller scale, numerous restraining releasing bends control the development of related folds (pop-up structures) and local basins (pull-apart basins and sags) along the San Clemente fault. Polyphase deformation is apparent along the fault where one large restraining bend, about 60 km long, is undergoing active uplift as indicated by shifting channels and Holocene-Pleistocene growth strata (Fig. 8). Superimposed upon this uplift are four smaller restraining-releasing bend pairs (about 4-8 km segments), mirroring the larger uplift at smaller scale. Several late Pleistocene regional stratigraphic marker beds can be correlated to nearby ODP sites where they have been dated (Janik, 2001). These markers allow kinematic modeling to determine the slip-rate of the fault, work presently in progress. At outcrop scale, DSV ALVIN observations of the San Clemente fault on the southeast flank of Navy Fan reveal a recent Holocene scarp 0.3-1.5 m in height (another 1-3 m in height from Legg's dive video, scarp taller than ALVIN). The scarp may be a single event scarp, suggested by the lack of multiple slope breaks and uniform "weathering" and bioturbation. The lightly bioturbated fresh scarp offsets Holocene and late Pleistocene strata, indicating a Holocene earthquake with a likely magnitude exceeding 6.5.

I. San Clemente fault section details

A. Santa Cruz - Santa Catalina Ridge [Figs. 1-2]

New multibeam bathymetry acquired late in year, future mapping effort

Mapping based on Greene and Kennedy (1987), Vedder et al, 1987), Junger and Vedder (unpublished mapping), Junger and Wagner (1977), Burdick and Richmond, 1982; Richmond et al, 1981

Complex zone with 2-3 subparallel fault zones bounding and within bathymetric ridge--transpressional(?); but subsiding in late Quaternary time (Goldfinger et al, 2001 unpublished)

Discontinuous, en echelon(?) fault traces based on widely spaced seismic profiles

Southeast more continuous segment--1981 Santa Barbara Island earthquake (**M**=6.0; Corbett, 1984; Bent and Helmberger, 1991)

Section boundary at major pull-apart basin and intersection with Catalina fault zone (Legg and Vedder, 1990)

Intersection with Western Transverse Ranges at Santa Cruz Island (Legg, et al, 2002)

B. San Clemente Island [Fig. 3 & 7]

Historically, one of first major faults recognized in California

Generally defined by east-facing San Clemente Island escarpment

Complete SeaBeam coverage (Legg et al, 1989; Legg, et al, 1998; Goldfinger et al, 2000)

Three major segments: northern and southern island, San Clemente basin

Northern mostly right-slip with some transtension; graben between escarpment and Emery Knoll

Southern has restraining bend for south half of island

San Clemente Basin and Fortymile Bank segment (Legg et al, 1989)

1951 San Clemente Island earthquake and Fortymile Bank seismicity -- backwards?

Relocations by Astiz and Shearer (2000), still poor depth control

C. Navy Basin [Figs. 3-4]

New SeaBeam data and submersible dives (Goldfinger et al, 2000)

Major transtensional section, step-over forming East San Clemente Basin (Legg, 1985)

Left separation of volcanic ridges suggest seafloor spreading and short transform faults (Legg, White and Macdonald, 2000)

Apparent change in fault trends from more westerly to current N40W (three trends visible)

D. Bend Region [Figs. 4, 6, 8, & 9]

Major restraining bend, subject of paper in preparation (Legg, Goldfinger, Einstein and Wang)

Escarpment across SW Navy Fan shows earthquake fault scarps 1-3 meters high, big earthquakes, recent pre-history

Major transpressional section, moderate to large earthquakes with tsunami potential

Uplift in Bend Region is very youthful, Quaternary, probably late Quaternary

Classic morphology of right-lateral wrench faulting

Important case study of active transpression in kilometer(s) thick "clay-cake" (turbidites)

Two prominent uplift peaks, different character, one bedrock core pop-up, other tilted sedimentary ridge

E. Descanso Plain - Ensenada Trough [Figs. 4-5]

Northern section of San Isidro fault zone (Moore, 1969; Legg, 1985)

Classic right-lateral "wrench" fault character in seismic profiles, flower structures

Alternating segments of transtensional sag basin faults and "pure" right-slip sections, with some small restraining bend "pop-ups"

Possible 4-km dextral offset of active Banda submarine fan (late Quaternary or younger)

Oblique, NW trending San Isidro Ridge fault zone, shows normal separation, not transpressional

F. San Isidro Basin [Fig. 1]

Main section of San Isidro fault zone (Moore, 1969)

Some seismic profiles and SeaBeam classic swaths along fault trend

Principal displacement zone (PDZ) along axis of transtensional basin

G. San QuintÌn - BahÌa Rosario [Fig. 1]

Fault zone primarily inferred from geomorphology, sags, saddles, linear valleys, scarps, etc.

2.2 *San Diego Trough fault system* Seven major recently-active fault sections of the San Diego Trough fault system are recognized (Tables I & II, Figs. 1-4). The northern part consists of two major sub-parallel fault zones: San Pedro Basin fault zone and Catalina fault zone. These two fault zones split from the main San Diego Trough fault zone beyond the southeast tip of the Santa Catalina Island platform (Fig. 3). The Santa Catalina Island platform (or tectonic block) represents a major restraining bend along the San Diego Trough fault zone, similar in size and character to the San Bernardino Mountains segment of the San Andreas fault. The Catalina fault zone merges with the Santa Cruz - Catalina Ridge section of the San Clemente fault system between the northwest end of the Santa Catalina Island platform and the northeast corner of the Santa Barbara Island platform. The San Pedro Basin fault zone consists of numerous discontinuous(?), en echelon, fault segments with prominent seafloor expression in Santa Monica Basin, and with well-defined offset of sub-seafloor acoustic horizons in the San Pedro Channel. The San Pedro Basin fault zone merges with the Catalina fault zone to form the San Diego Trough fault zone at a pull-apart basin adjacent to Crespi Knoll (Fig. 3) and a few kilometers northwest of the 1986 Oceanside earthquake epicentral zone. The San Diego Trough fault zone is well-defined in seismic profiles and with seafloor expression including low fault scarps cutting across the active La Jolla and Pleistocene Coronado submarine fans (Fig. 5; Kennedy et al, 1980; Legg, 1985). Like other major right-slip fault zones in southern California, notably the Imperial and Cerro Prieto faults in the Salton Trough, the San Diego Trough fault zone is narrow, continuous, and relatively straight for a length approaching 100-150 km. Right-slip character is manifest as small transpressional uplifts (pop-up structures) at left bends or fault offsets (Fig. 3) and transtensional sags or pull-apart basins at right bends or step-overs. To the south, the San Diego Trough fault zone continues across the active Shepard (Pta. Salsipuedes) and Banda submarine fans (Fig. 4) before turning more to the southeast to merge with the South Branch of the Agua Blanca fault in Bahia Soledad at Punta Santo Tomas. The new multibeam bathymetric grid shows well imaged bathymetric piercing point offsets that demonstrate right-oblique separation of ~32 km between Thirtymile Bank and Coronado Bank.

II. San Diego Trough fault section details

A. San Pedro Basin fault zone [Figs. 1-2]

Mapping based on Greene and Kennedy (1987), Vedder et al, 1987), Junger and Vedder (unpublished mapping), Junger and Wagner (1977) with some USGS site surveys

Discontinuous, en echelon(?) fault traces based on widely spaced seismic profiles

Abundant microseismicity over a broad zone 20 km wide

B. Santa Catalina Island [Fig. 3]

Major restraining bend with "pop-up" structure

Likely northeast-dipping, oblique-reverse faulting on southwest flank of uplift

Age of island uplift remains to be determined

Major tsunami source potential, subject of ongoing research

C. Gulf of Santa Catalina [Fig. 3]

Southern continuation of San Pedro Basin fault zone

San Pedro Basin fault zone and Catalina fault zone merge at Crespi Knoll

D. San Diego Trough [Fig. 4]

Narrow (<~1 km), straight (N30W), well-defined, long (>120 km) and continuous fault cuts active La Jolla and late Pleistocene Coronado submarine fans

Low seafloor scarps, 7-10 m high extend 10s of km across active fan surfaces

Minor restraining bend uplifts occur at left bends and step-overs at northern end of San Diego Trough, Coronado fan, and west of Bahia Descanso show right-slip character

Multichannel seismic profiles suggest that high-angle San Diego Trough fault offsets ancient low-angle Thirtymile Bank detachment fault (Legg et al, 1992)

Moderate earthquake with rich aftershock sequence at northern end, offshore Oceanside (1986, M_S=5.8) may be related to high stress at restraining bend and re-activation of dismembered Thirtymile Bank detachment fault as blind thrust (Rivero et al, 2000)

E. Descanso Plain [Fig. 4]

Southern continuation of San Diego Trough fault zone cuts active (Holocene) Shepard and Banda submarine fans

Fault offsets and/or deflects major submarine fan valleys providing candidate piercing points for quantifying right-slip and rate

F. BahÌa Soledad [Fig. 4]

Fault turns to southeast to merge with South Branch of the Baja Peninsula Agua Blanca fault

Systematic northeast-side up observed in high-resolution seismic profiles may imply that fault has oblique-reverse character (Legg, 1985)

G. Punta Santo Tom·s [Fig. 1]

Inferred continuation of offshore fault at base of escarpment along Soledad Ridge and Cabras Bank (Legg, 1985) may have oblique-normal character

Fault zone parallel to and along northeast flank of San Isidro Basin may continue undetermined distance to southeast offshore Baja California

2.3 *Recency of Faulting* Recency of fault movement was determined by the geomorphic expression of the fault from the multibeam bathymetry combined with identification of the youngest seafloor sediments deformed or disrupted by faulting as imaged in high-resolution seismic reflection profiles. Without detailed sub-bottom stratigraphic information from well logs or core holes, a simple seismic stratigraphic sequence was used including: 1) Holocene; 2) Late Quaternary (assumed to be less than about 750 ka); 3) Pleistocene; 4) Plio-Pleistocene; and pre-Pliocene. In general, Holocene sediments are recognized by acoustic transparency in very high resolution (3.5 kHz) seismic profiles, due to the unconsolidated and water-saturated character of this most recent sediment drape. This corresponds to unconsolidated olive-green mud retrieved in multicores in 1999 and 2000 cruises. The other sequence ages were determined from the scattered piston core, dart core and other sub-bottom sampling information available in published sources (Emery, 1960; Vedder et al, 1974; Vedder, 1990; Dunbar, 1981). Where fault traces have well-defined seafloor expression including fault scarps in youthful sediments, activity is inferred to be Holocene. If the well-defined seafloor expression occurs in older bedrock materials, the recency is inferred to be late Quaternary or younger; more subtle seafloor fault morphology in bedrock areas is considered pre-Quaternary based on the age of the outcrop. Most of the major fault zones mapped in this project show abundant evidence of late Quaternary activity, and locally Holocene fault movement. These results are consistent with prior mapping by the U.S. Geological Survey (Vedder et al, 1974) and the California Division of Mines and Geology (Greene and Kennedy, 1986; Kennedy et al, 1980; 1987; Vedder et al, 1986; Clarke et al, 1987). Pleistocene datums, notably a stage 5E reflector, have been correlated from ODP drilling in East Cortez Basinnusing oxygen isotope data matched to prominent reflectors. The stage 5e reflector is present in south San Clemente Basin, and is folded in the restraining bend structure discussed above. We are presently modeling the vertical and horizontal deformation of this feature to extract the post-5e slip rate of the San Clemente fault.

2.3 *Fault Character* Character of faulting was inferred from the seafloor geomorphology and fault geometry in map view and cross-section imaged in seismic profiles. In general, the major fault zones mapped for this study are right-slip in character based upon the following observations.

The fault traces are generally very straight, with well-defined, narrow, and continuous zones of faulting across high relief bathymetry (Figs. 3, 4, 7, & 8). The straight surface (seafloor) trace of these faults are consistent with high-angle, sub-vertical faulting at depth. Multichannel seismic profiles confirm the sub-vertical fault character in numerous places where the major faults are crossed (Bohannon and Geist, 1998; Legg et al, 1992).

The fault morphology shows character consistent with dextral strike-slip at fault bends and offsets. At right steps or bends, sagging of sedimentary sequences into the fault zone, with secondary normal separation faulting that shows extensional or transtensional character, consistent with pull-apart or sag basin formation (Fig. 5, line B-32). At left steps or bends, fault-normal shortening is evident as folding and secondary thrust or reverse faulting with seafloor uplift apparent that shows convergent or transpressional character (Fig. 6). Areas of oblique movement, both transtensional or transpressional, are generally broader zones of faulting than more straight and narrow, inferred pure, strike-slip fault segments (Fig. 5, line B-30). In some places, geomorphic features such as submarine fans and channels, landslides or debris flows appear to be offset or deflected in a right-lateral manner, consistent with right-slip faulting. There are some prominent branch or secondary fault segments that show seafloor uplift and consistent normal separation in seismic profiles, such as San Isidro Ridge (Fig. 4; Legg, 1985). These are inferred to be normal or oblique-normal fault segments. Other major branch or secondary fault segments show seafloor uplift, folded sedimentary sequences and reverse separation, such as along the Bend Region of the San Clemente-San Isidro fault zone. These are inferred to be reverse or oblique-reverse fault segments.

2.4 *Earthquake Potential* Based upon fault segment and section lengths that exceed 100 km in many cases, both major fault systems are capable of large (Moment Magnitude, **M** > 7) earthquakes (Tables I & II). Individual segments, if using a characteristic earthquake model, are capable of maximum magnitudes ranging from **M**=6.5 to **M**=7.3. Multisegment ruptures (cascades) may occur, bringing the maximum magnitudes to **M**~7.6. The overall length of the San Clemente fault system exceeds that of the 1906 San Andreas fault rupture, and recent earthquakes onshore southern California like Landers (1992) and Hector Mine (1999) show than multiple segment fault ruptures are typical of the region. A large multisegment rupture cannot be dismissed, and existing data are insufficient to address this issue. The largest historic earthquakes in the southern California offshore region are moderate, **M**≥6 based upon recent detailed seismology studies (Bent and Helmberger, 1991; Cruces and Rebollar, 1991). Of the three largest events, only the 1981 Santa Barbara Island earthquake (**M**=6.0) had a significant aftershock sequence showing rupture along part of the Santa Cruz - Catalina Ridge section of the San Clemente fault system (Corbett, 1984; Bent and Helmberger, 1991; Astiz and Saldivar, 2000). The December 26, 1951 San Clemente Island (M_L=5.9) and the December 22, 1964 Offshore Ensenada (M_S=6.2) earthquakes were almost devoid of aftershocks (Legg, 1980; Cruces and Rebollar, 1991). In contrast, the July 13, 1986 Oceanside (M_S=5.8) earthquake had the richest aftershock sequence, for its size, of any earthquake recorded in southern California history (Hauksson and Jones, 1988). These wide variations in aftershock patterns may represent significant differences in tectonic style for the events (thrust versus strike-slip mechanisms) or important changes in the spatial and temporal evolution of regional seismotectonics that remain to be resolved.

The width of the seismogenic faulting must be determined for more accurate estimation of earthquake potential. For sub-vertical strike-slip faulting, the depth of the seismogenic zone as determined from microseismicity or earthquake aftershock studies provides a direct measure of the seismogenic crustal thickness. Unfortunately, for most earthquake located offshore southern California, the distribution of seismograph stations is poor for accurate hypocentral locations. Special studies of larger earthquake sequences or microseismicity in particularly active areas are needed to estimate the thickness of the seismogenic crust. Although absolute depths of earthquake foci are typically uncertain by about 2-5 km for even the best located events, using master event techniques, etc., the relative locations of all aftershocks or events in major sequences are accurate to 1 km or less (Corbett, 1984; Hauksson, 1987; Hauksson and Gross, 1988; Magistrale, 1993; Astiz and Shearer, 2000). Therefore, the thickness of the seismogenic zone is at least as great as the relative vertical distribution of these well-located earthquake sequences. From these published studies, the thickness of the seismogenic zone in the Inner California Continental Borderland appears to be similar to that of subaerial southern California fault zones, about 15-20 km. The areas where seismicity appears to occur deeper in the offshore area include the Santa Barbara Channel and Western Transverse Ranges, Santa Monica Basin (Hauksson and Saldivar, 1986; 1989), and along the Santa Cruz-Catalina Ridge where the 1981 Santa Barbara Island earthquake occurred (Corbett, 1984). There also appears to be somewhat deep seismicity in the Fortymile Bank area (Astiz and Shearer, 2000). The top of the seismogenic zone is assumed to be at or near the seafloor, which has a real earth depth of typically 1-2 km for the study area.

The crustal thickness or depth to Moho constrains the seismogenic thickness of the crust. Based upon seismic refraction studies in the area (Shor and Raitt, 1958; Shor et al, 1976; Corbett, 1984), the crustal thickness is about 24 km in the central part of the Inner Borderland. This is somewhat thinner than the crust of the Peninsular Ranges or Transverse Ranges, and a higher heat flow associated with thinner crust would tend to raise the depth of the brittle-ductile transition zone in typical basement rocks. The observation that earthquake foci may be equally deep in the Inner Borderland as they are in the mountainous continental crust of the adjacent Peninsular Ranges may imply that the rheology of the Borderland crust is somewhat different than that of the Peninsular Ranges. One possible difference may be the presence of water, in hydrated basement rocks of the Inner Borderland (Catalina Schist including serpentinite). Alternatively, the true focal depths of offshore earthquakes are shallower than inferred from the existing seismological studies. The presence of very shallow basement rocks, with higher seismic velocity near the hypocenter, would move earthquake locations made with 1-D models deeper. This important issue remains to be settled by direct recording of offshore earthquakes with Ocean Bottom Seismometers (OBS) in the near source zone, or with more accurate 3-D seismic velocity structure and ray tracing in the event location process.

2.5 *Slip Rate and Recurrence* Slip rates and recurrence intervals for major earthquakes on the offshore faults may be determined from measured offset of prominent geomorphic features or seismic sequences that provide piercing points to record the strike-slip. For the first year of this project, the focus was to map the fault traces, and identify candidate piercing points to be more thoroughly investigated in the subsequent project. The main offset features identified to date include submarine fan and channel features offshore northern Baja California (Legg, 1985), major seafloor uplift in the Bend Region of the San Clemente-San Isidro fault zone (restraining bend), and submarine landslides on the flank of Fortymile Bank (Legg and Kamerling, 2002). A preliminary slip-rate of about 4-7 mm/yr for the San Clemente and San Isidro fault zones was presented by Legg (1985) based upon the offset of the late Quaternary Banda submarine fan and inferred debris flow deposits in North San Clemente Basin. This value is tentatively used as 5.0±2 mm/yr for the only "poorly" constrained slip rate for these major offshore fault systems. Multiple seafloor scarps of various ages, including some that clearly offset Holocene sediments, were observed from the DSV Alvin in the vicinity of Navy Fan (Goldfinger et al, 2000). These scarps show that there have been multiple moderate to large earthquakes with seafloor fault rupture along the San Clemente fault in late Quaternary and Holocene time. Further study is needed to constrain timing and frequency of these events. The most critical needs are for further high-resolution imaging, and for dated late quaternary stratigraphy to define the ages of offset or deformed features.

2.6 *Tsunami Potential* Elastic dislocation modeling of the Bend Region along the San Clemente - San Isidro fault zone, located about 60 km southwest of San Diego, tends to underestimate the seafloor uplift expected from large earthquakes on this fault. For a maximum oblique-reverse displacement of about 4 meters at the focal depth (12 km) on the fault plane, only about 40 cm of seafloor uplift is predicted. In contrast, recent large right-slip earthquakes in southern California like Landers (1992) and Hector Mine (1999) show areas with 4-8 meters of oblique right-slip in some areas. Clearly anelastic deformation probably dominates deformation within the restraining bend, and must be modeled to assess tsunami potential. Observations from the submersible DSV Alvin showed youthful seafloor scarps that appear to be single-events based upon lack of significant bioturbation or sediment cover that reach 1-3 meters in height. Consequently, the maximum displacement was set to about 8 meters at the focal depth to derive about 2 meters of seafloor uplift for tsunami generation. Using the tsunami generation, propagation, and run-up codes at the University of Southern California (Legg and Borrero, 2001), we determined that the maximum run-up along the adjacent southern California and northern Baja California coast would be approximately equal to the maximum seafloor uplift, about 2 meters (Figs. 9-10). Tsunami travel time to Point Loma was about 15 minutes, too short for an official warning to be issued from the U.S. West Coast and Alaska Tsunami Warning Center via the California OES.

3. **References**:

Astiz, L. and Shearer, P.M., 2000, Earthquake locations in the inner Continental Borderland offshore southern California: Seismological Society of America Bulletin, v. 90, p. 425-449.

Bennett, R.A., Rodi, W., and Reilinger, R.E., 1996, Global Positioning System constraints on fault slip rates in southern California and northern Baja, Mexico: *Jour. Geophys. Res.*, v. 101, p. 21,943-21,960.

Bent, A. L., and Helmberger, D. V., 1991, Seismic characteristics of earthquakes along the offshore extension of the Western Transverse Ranges, California: Seismological Society of America Bulletin, v. 81, p. 399-422.

Bohannon, R. G., Eittreim, S. L., and CHilds, J. R., 1990, Cruise report of R/V S.P. Lee, Leg 4, 1990a, California continental borderland: U.S. Geological Survey Open-File Report OF 90-0502, 10 p.

Bohannon, R., Eittreim, S., Childs, J., Geist, E., Legg, M., Lee, C., Sorlien, C., and Busch, L., 1990b, A seismic-reflection study of the California Continental Borderland, [abstract] *in* Trans. American Geophysical Union, v. 71, p. 1631.

Bohannon, R. G., and Geist, E., 1998, Upper crustal structure and Neogene tectonic development of the California Continental Borderland: Geological Society of America Bulletin, v. 110, p. 779-800.

Burdick, D. J., and Richmond, W. C., 1982, A summary of geologic hazards for proposed OCS oil and gas lease sale 68, southern California: U.S. Geological Survey Open-File Report 82-33.

Clarke, S. H., Greene, H. G., Kennedy, M. P., and Vedder, J. G., 1987, Geologic map of the inner-southern California continental margin: California Division of Mines and Geology, California Continental Margin Geologic Map Series, Area 1 of 7, sheet 1 of 4, scale 1:250,000.

Corbett, E. J., 1984, Seismicity and crustal structure studies of southern California: Tectonic implications from improved earthquake locations: [Ph.D. dissertation] California Institute of Technology, Pasadena, California, 231 p.

Cruces, F. J., and Rebollar, C. J., 1991, Source parameters of the 22 December 1964 (m_b=5.4, M_S=6.2) offshore Ensenada earthquake: Physics of the Earth and Planetary Interiors, v. 66, p. 253-258.

Dunbar, R.B., 1981, Sedimentation and the history of upwelling and climate in high fertility areas of the northeastern Pacific Ocean [Ph.D. thesis]: San Diego, Scripps Institution of Oceanography.

Emery, K. O., 1960, The Sea Off Southern California, A Modern Habitat of Petroleum: John Wiley & Sons, Inc., New York, New York, 366 p.

Greene, H.G., and Kennedy, M.P., 1987, Geology of the California continental margin: Explanation of the California continental margin geologic map series: California Division of Mines and Geology Bulletin 207, 110 p.

Hauksson, Egill, 1987, Seismotectonics of the Newport-Inglewood fault zone in the Los Angeles basin, southern California: Seismological Society of America Bulletin, v. 77, p. 539-561.

Hauksson, Egill, 1990, Earthquakes, faulting, and stress in the Los Angeles basin: Journal of Geophysical Research, v. 95, p. 15,365-15,394.

Hauksson, Egill, and Jones, L. M., 1988, The July 1986 Oceanside (M_L=5.3) earthquake sequence in the continental borderland, southern California: Seismological Society of America Bulletin, v. 78, p. 1885-1906.

Hauksson, Egill, and Saldivar, G. V., 1986, The 1930 Santa Monica and the 1979 Malibu, California, earthquakes: Seismological Society of America Bulletin, v. 76, p. 1542-1559.

Hauksson, Egill, and Saldivar, G. V., 1989, Seismicity and active compressional tectonics in Santa Monica Bay, southern California: Journal of Geophysical Research, v. 94, p. 9591-9606.

Janik, A., 2001, Pleistocene sedimentation in the outer basins of the California borderlands from digitally-acquired 3.5 kHz subbottom profiles and ODP Leg 167 drilling: [abstract] Trans. American Geophysical Union, v. 82, p. F740.

Jennings, C. W., 1994, Fault activity map of California and adjacent areas: California Division of Mines and Geology, Map No. 6, scale 1:750,000.

Junger, Arne, and Wagner, H. C., 1977, Geology of the Santa Monica and San Pedro Basins, California Continental Borderland: U. S. Geological Survey, Miscellaneous Field Studies, Map MF-820, Scale 1:250,000.

Kennedy, M. P., Clarke, S. H., Greene, H. G., and Legg, M. R., 1980, Recency and character of faulting offshore metropolitan San Diego, California: California Division of Mines and Geology, Map Sheet 42, Scale 1:50,000.

Kennedy, M. P., Greene, H. G., and Clarke, S. H., 1987, Geology of the California continental margin: Explanation of the continental margin geologic map series: California Division of Mines and Geology Bulletin 207, 110 p.

Larson, K.M., 1993, Application of the Global Positioning System to crustal deformation measurements, 3, Result from the southern California borderlands: *Jour. Geophys. Res.*, v. 98, p. 21,713-21,726.

Legg, M. R., 1985, Geologic Structure and tectonics of the inner continental borderland offshore northern Baja California, Mexico [unpublished Ph.D. dissertation]: University of California, Santa Barbara, Santa Barbara, California, 410 p.

Legg, M.R., and Borrero, J.C., 2001, Tsunami potential of major restraining bends along submarine strike-slip faults: *in* Proceedings of the International Tsunami Symposium 2001, NOAA/PMEL, Seattle, WA, p. 331-342.

Legg, M.R., and Kamerling, M.J., 2002, Large-scale basement-involved landslides, California Continental Borderland: in Watts, P., Synolakis, C.E., and Bardet, J.-P., eds., *Prediction of Underwater Landslide Hazards*, Proceedings of the May 2000 Workshop, University of Southern California, Balkema Press (in press).

Legg, M.R., and M.P. Kennedy, 1991, Oblique divergence and convergence in the California Continental Borderland. *in* Abbott, P.L., and W.J. Elliott, eds., Environmental Perils of the San Diego Region. San Diego Association of Geologists Guidebook, p. 1-16.

Legg, M.R., and J. G. Vedder, 1990, Pull-apart basins along the San Clemente fault, offshore southern California: [Abstract] *in* Trans. American Geophysical Union, v. 71, Fall Meeting, San Francisco, CA, p. 1631.

Legg, M.R., B.P. Luyendyk, J. Mammerickx, C. de Moustier, and R.C. Tyce, 1989, Sea Beam survey of an active strike-slip fault: The San Clemente fault in the California Continental Borderland. *Journal of Geophysical Research*, v. 94, p. 1727-1744.

Legg, M. R., Wong-Ortega, V., and Suarez-Vidal, F., 1991, Geologic structure and tectonics of the inner continental borderland of northern Baja California. *in* Dauphin, P., and G. Ness, editors, The Gulf and Peninsular province of the Californias. American Association of Petroleum Geologists Memoir #47, p. 145-177.

Legg, M.R., C. Nicholson, and C. Sorlien, 1992, Active faulting and tectonics of the inner California Continental Borderland. [Abstract] *In* Trans. American Geophysical Union, v. 73, p. 588.

Legg, M.R., Einstein, D.E., and Wang, H.D., 1999, Deformation history of a major restraining bend along a right-slip fault: the San Clemente fault offshore northern Baja California: SCEC Annual Meeting, Palm Springs, CA, p. 74.

Legg, M.R., White, S., and Macdonald, K., 2000, Late Cenozoic seafloor spreading in South San Clemente Basin: A hole through the Inner Borderland lithosphere: [Abstract] Trans. American Geophysical Union, Fall meeting, San Francisco, p. 1068.

Magistrale, H., 1993, Seismicity of the Rose Canyon fault zone near San Diego, California: Bulletin of the Seismological Society of America, v. 83, p. 1971-1978.

Moore, D. G., 1969, Reflection profiling studies of the California Continental Borderland Structure and Quaternary turbidite basins: Geological Society of America Special Paper 107, 142 p.

Moore, G. W., and Beyer, L. A., 1975, Seismic reflection profiles, R/V KELEZ, November-December 1973, continental borderland of southern California: U.S. Geological Survey Open-File Report 75-330, 43. p.

Richmond, W. C., Cummings, L. J., Hamlin, S., and Nagaty, M. E., 1981, Geologic hazards and constraints in the area of proposed OCS oil and gas Lease Sale 48, southern California: U.S. Geological Survey Open-File Report 81-307.

Rivero, C., Shaw, J.H., and Mueller, K., 2000, Oceanside and Thirtymile Bank blind thrusts: Implications for earthquake hazards in coastal southern California: Geology, v. 28, p. 891-894.

Shepard, F. P., and Emery, K. O., 1941, Submarine topography off the southern California coast--Canyons and tectonic interpretation: Geological Society of America Special Paper 31, 171 p.

Shor, G. G., Jr., and Raitt, R. W., 1958, Seismic studies in the southern California borderland: Congreso Geologico Internacional, XXa Seccion, 1956, Mexico, Seccion IV, Segundo Tomo, p. 243-259.

Shor, G. G., Jr., Raitt, R. W. and McGowan, D. D., 1976, Seismic refraction studies in the southern California borderland, 1949-1974: Scripps Institute of Oceanography Reference 76-13, 70 p.

Smith, D.L., and W.R. Normark, 1976, Deformation and patterns of sedimentation, south San Clemente Basin, California borderland: Marine Geology, v. 22, p. 175-188.

U.S.G.S., 1996, Probabilisitic seismic hazard assessment for the State of California: U.S. Geol. Survey Open-File Report 96-08.

Vedder, J. G., 1975, Acoustic reflection profiles, R/V Kelez, May-June 1973, leg 3, offshore southern California: U.S. Geological Survey Open-File Report 75-265, scale 1:250,000.

Vedder, J. G., 1990, Maps of California Continental Borderland showing compositions and ages of bottom samples acquired between 1968 and 1979: U.S. Geological Survey Miscellaneous Field Studies Map MF-2122, three sheets, scale 1:250,000.

Vedder, J. G., Beyer, L. A., Junger, Arne, Moore, G. W., Roberts, A. E., Taylor, J. C., and Wagner, H. C., 1974, Preliminary report on the geology of the Continental Borderland of southern California: U.S. Geological Survey, Miscellaneous Field Studies *Map MF-624*, Scale 1:500,000.

Vedder, J. G., Greene, H. G., Clarke, S. H., and Kennedy, M. P., 1986, Geologic map of the mid-southern California continental margin: California Division of Mines and Geology, California Continental Margin Geologic Map Series, Area 2 of 7, sheet 1 of 4, scale 1:250,000.

Wells, D.L., and Coppersmith, K.J., 1994, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement: *Bull. Seism. Soc. Am.*, v. 84, p. 974-1002.

5. **Reports Published**

Legg, M.R., Kuhn, G.G., and Slosson, J.E., 2000, Seismic hazard assessment along tectonically active coasts: [Abstract] Geological Society of America, 2000 Annual Meeting, Reno, NV.

Legg, M.R., 2000, California Continental Borderland: Nature's excellent laboratory for interacting tectonic, biological, and geochemical processes: [Abstract] in Trans. American Geophysical Union, Fall meeting, San Francisco, p. 1067-1068.

Legg, M.R., White, S., and Macdonald, K., 2000, Late Cenozoic seafloor spreading in South San Clemente Basin: A hole through the Inner Borderland lithosphere: [Abstract] Trans. American Geophysical Union, Fall meeting, San Francisco, p. 1068.

Goldfinger, C., M. Legg, and M. Torres, 2000, New mapping and submersible observations of recent activity of the San Clemente fault: [Abstract] Trans. American Geophysical Union, Fall meeting, San Francisco, p. 1069.

Legg, M.R., and Borrero, J.C., 2001, Tsunami potential of major restraining bends along submarine strike-slip faults: in Proc. International Tsunami Symposium 2001, NOAA/PMEL, Seattle, WA, p. 331-342.

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Figure 2. Seismic reflection tracklines (partial) for the project area. New 3.5 kHz digital data collected on R/V Atlantis in 1998, 1999, and 2000 not shown. Solid lines are analog single channel profiles; dashed lines are digital MCS profiles; red lines are faults.

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Figure 3. Map showing major fault segments in the San Clemente and Santa Catalina Island region. Fault symbology explained in legend of Fig. 4. Only the major faults of the San Clemente and San Diego Trough fault systems are shown.

Figure 4. Map showing major fault segments in the San Diego Trough and Descanso Plain region. Only the major faults of the San Clemente and San Diego Trough fault systems are shown. Regional bathymetry after Legg (1985).

Figure 5. Sparker seismic profile (Line B-30'-31-32) across the Descanso Plain southwest of Punta Salsipuedes (see Fig. 4 for profile location). Note the numerous seismic sequences which can be identified in the slope and basin sediments. Two course changes (C/C) are present along this profile. Acoustic facies are identified by name, except for the older slope and basin sediments shown by the regular dot pattern. San Isidro fault zone shows transtensional character on line B-30 (left) and pure strike-slip character on line B-32 (center). San Diego Trough fault shows pure strike-slip character on line B-32 (right). Salsipuedes fault is part of the Coronado Bank - Agua Blanca fault zone (Source: Legg, 1985).

Figure 6. Sparker profile across the Bend Region of the San Clemente fault near the Descanso Plain. Horizon "Base PEL" is the base of "hemipelagic" unit described by Smith and Normark (1976) of late Pleistocene age (about 470 ka; Legg, 1985).

Figure 7. Perspective shaded relief bathymetric image (100 m grid) showing the right-lateral offset of San Clemente Island and Fortymile Bank along the San Clemente fault zone (SCFZ). View is looking south, lighting is from the southwest, and vertical exaggeration = 4. Large dextral offset of the Thirtymile Fortymile Bank block along the San Clemente fault is ~ 60 km. Large dextral, oblique-normal, offset of Thirtymile Bank from Coronado Bank across San Diego Trough is also apparent and is ~36 km.

Figure 8. Perspective shaded relief bathymetric image (100 m grid) showing the southern segment of the San Clemente fault (Bend Region). View is looking NW, lighting is from the SW, and vertical exaggeration = 4. This segment contains several releasing and restraining bends, resulting in pairs of extensional and compressional features. Note the channel at left, which abandoned levees indicate, has been forced westward by growth of the uplift.

Figure 9. Location map and run-up plot for tsunami simulation at the Bend Region, San Clemente fault zone. The thick black lines are the seismic deformations associated with the earthquake. The run-up along the coast is plotted on the right (Legg and Borrero, 2001).

Figure 10. Synthetic wave gauge record off Point Loma, near the entrance to San Diego Bay, for the tsunami simulation above. A water surface fluctuation of over 1 m is modeled, and tsunami travel time is about 15 minutes, too short for official warning (Legg and Borrero, 2001).