Earthquake Potential of Major Faults Offshore Southern California:
Collaborative Research with Oregon State University and Legg Geophysical

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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

1. Investigations Undertaken

1.1 *Fault Mapping*

Prepare large-scale maps of seafloor bathymetry from SeaBeam and dense echo-sounding grids
Compile and interpret existing seismic reflection profiles to determine fault character, recency, dip
Map active fault traces using seafloor geomorphology and seismic profiles
Import fault maps into Geographic Information System
Prepare publication-quality map preparation and 3-D perspective views of seafloor deformation

1.2 *Earthquake Potential, Magnitude and Segmentation*

Compile and interpret seismic refraction and microseismicity data for fault depth, thickness
Determine Maximum Magnitude based on fault length and area from empirical data
Define major fault segments, boundaries, character and "characteristic" earthquake magnitudes

1.3 *Slip Rates and Recurrence Interval*

Identify candidate piercing points
Compile and interpret 3.5 kHz data for Recent (late Quaternary) deformation
Contour isopachs and structural elevations of late Quaternary and Holocene horizons
Estimate stratigraphic ages based upon existing piston cores in area
Compare geologic with geodetic and seismicity estimates of slip rates

1.4 *Tsunami Potential*

Identify areas and character of oblique faulting with seafloor uplift/subsidence
Contour isopachs and structural elevations to quantify uplift or subsidence rates
Elastic dislocation modeling for single-event deformation, tsunami and earthquake potential

2. Results

2.1 *San Clemente Fault System*—Seven major recently-active fault sections of the San Clemente fault system are recognized (Table Ia, Figure 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. 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 (Fig. 2) 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. The Descanso Plain segment is transtensional, with downwarping of late Pleistocene sediments into an elongate trough (sag) aligned with the main fault traces. 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.

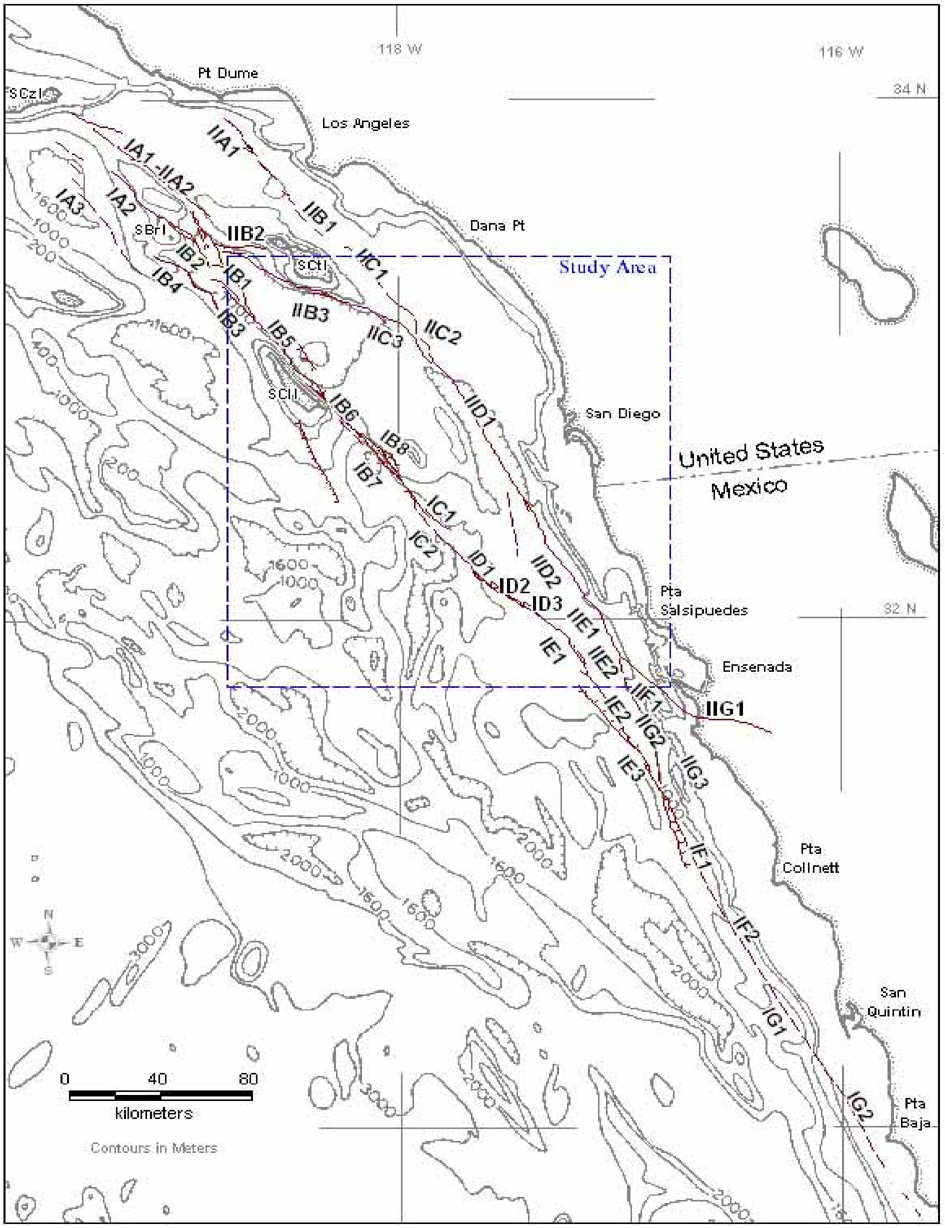

Figure 1. Map showing major sections and segments of the San Clemente and San Diego Trough fault systems (Table I). SCzI = Santa Cruz Island; SCtI = Santa Catalina Island; SBrI = Santa Barbara Island; SClI = San Clemente Island.

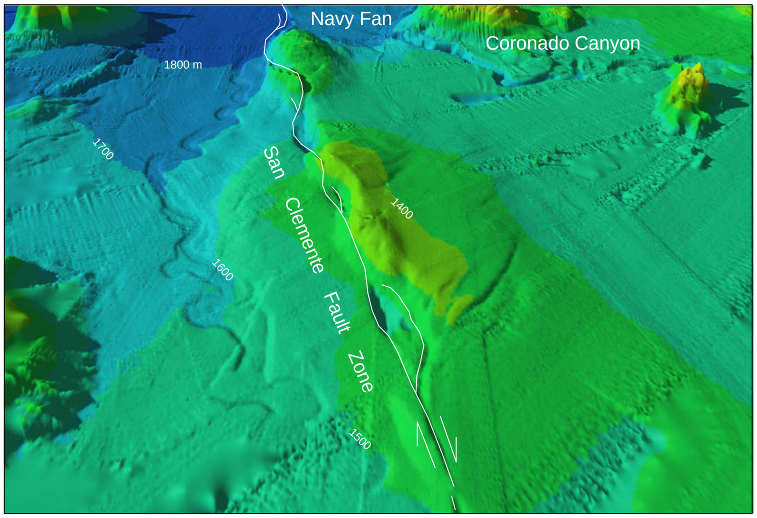

Figure 2: Perspective shaded relief bathymetric image (100 m grid) showing the southern segment of the San Clemente Fault. View is looking NW, lighting is from the SW, and vertical exaggeration = 4. This segment contains several releasing and restraining bends, resulting in pairs of extensional and compressional features. Note the channel at left, which abandoned levees indicate, has been forced westward by growth of the uplift.

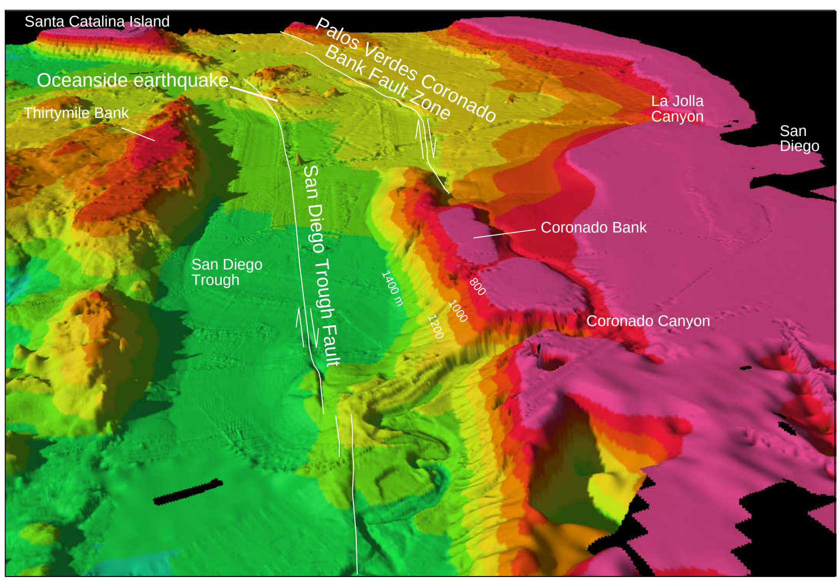

Figure 3: Perspective shaded relief bathymetric image (100 m grid) of the San Diego Trough Region of the Southern California Borderlands, offshore San Diego. View is looking N, lighting is from the SW, and vertical exaggeration = 4. Both faults are expressed at he seafloor and can be imaged even with Seabeam using a 100 m grid. The San Diego trough fault offsets the Coronado Canyon, and at upper center has generated a pushup feature at a restraining bend. This is the site of the Oce anside earthquake.

Three recent cruises to the southern San Clemente fault in the southern California borderland focused on active tectonic and bio-geologic processes associated with this major offshore fault system. We have combined new multibeam data collected in 1998-2000 with existing multibeam and sounding data to produce a new bathymetric grid for the southern borderland. The new grid reveals both broad and fine scale tectonic geomorphic relationships along the San Clemente, San Diego Trough and other fault systems. The dominant dextral nature of the borderland faults is revealed by offset drainages, offset basement highs, and the numerous restraining and releasing bends 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 some 60 km from the submerged Fortymile Bank to the east. On a smaller scale, numerous restraining and releasing bends control the development of related folds along the San Clemente fault. Polyphase deformation is apparent along the fault where one restraining bend is undergoing active uplift as indicated by shifting channels and Holocene-Pleistocene growth strata. Superimposed on this uplift are four smaller restraining-releasing bend pairs, mirroring the larger uplift at a smaller scale. Several late Pleistocene regional stratigraphic marker beds can be correlated to nearby ODP sites where they have been dated. These markers allow kinematic modeling to determine the slip-rate of the fault, work presently in progress. At outcrop scale, ALVIN observations of the San Clemente fault on the northern flank of Navy Fan reveal a recent Holocene scarp 0.3-1.5 m in height. 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 event that likely had a magnitude greater than 6.

2.2 *San Diego Trough Fault System*—Seven major recently-active fault sections of the San Diego Trough fault system are recognized (Table Ib, Fig.1). 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. 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 discontinous(?), 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 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. 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 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 extensional separation of ~ 32 km between Thirtymile Bank and Coronado Bank.

2.3 *Earthquake Potential* Based upon fault segment and section lengths that exceed 100 km in many cases, both major fault systems are capable of large (Magnitude > 7) earthquakes. 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 be possible, bringing the maximum magnitude 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 that multiple segment fault ruptures are typical of the region. A large multisegment rupture cannot be ruled out, and existing data are insufficient to address this issue. The largest historic earthquakes in the southern California offshore region are moderate, $M \geq 6$ based upon recent detailed seismology studies. 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. 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.

2.4 *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 (Fig. 4). 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.

2.5 References

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 Science Letters*, v. 66, p. 253-258.

Hauksson, E. 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.

Legg, M.R., 1980, Seismicity and Tectonics of the Inner Continental Borderland of Southern California and Northern Baja California, Mexico: M.S. Thesis, Univ. California, San Diego.

3. Non-technical Summary

The San Clemente and San Diego Trough fault systems are major active earthquake sources submerged offshore southern California. Both are right-lateral strike-slip faults, with mostly horizontal fault movements. Large earthquakes, Magnitude > 7, that may occur on these faults would damage structures and lifeline facilities in coastal southern California. Large seafloor fault scarps likely record large earthquakes that occurred in recent prehistory (probably <1,000 years). Major seafloor uplift at fault bends where the horizontal movement is impeded (restraining bends) may generate local tsunami that would strike the coast in a time too short (<10-20 minutes) for official warnings to be issued.

4. 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.

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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.

5. **Data Availability**

When the project is completed, Multibeam Bathymetry may be released through the NOAA data center and/or the Scripps Geologic Data Center.

Digital fault maps will be available through the Southern California Earthquake Center in the CFM, version A.

Seismic reflection profiles (microfilm copies) are available from the original sources including the U.S. Geological Survey and the Scripps Institution of Oceanography Geologic Data Center.

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Table Ia. Major Fault Sections and Segments – San Clemente Fault System.
[Fault sections in *italics*; **ID** corresponds to Figure 1]

ID	Fault Name	Length (km)	M_{max}
I	**San Clemente Fault System**	>590	8.0
IA	*Santa Cruz – Catalina Ridge*	90-95	7.4
IA1	Santa Cruz – Catalina Ridge	75	7.2
IA2	Pilgrim Banks – Santa Barbara Island	85	7.3
IA3	East Santa Cruz Basin	80+	7.3+
IB	*San Clemente Island*	130-160	7.6
IB1	North Catalina Basin	30	6.8
IB2	Kimki	25	6.7
IB3	San Clemente Ridge	25	6.7
IB4	Osborn Bank	35-40	6.9
IB5	San Clemente Escarpment	60	7.2
IB6	San Clemente Canyon	45	7.0
IB7	North San Clemente Basin	25	6.7
IB8	Junger	20-56	6.5-7.0
IC	*Navy Basin*	30-35	6.9
IC1	Navy Basin	30-35	6.9
IC2	San Salvador Knoll	15-35	6.5-6.9
ID	*Bend Region*	60	7.2
ID1	Navy Fan	10-25	6.7
ID2	Northwest Uplift	15-18	6.6
ID3	Southeast Uplift	20-25	6.7
IE	*Descanso Plain – Ensenada Trough*	80-85	7.3
IE1	South Descanso Plain	20-25	6.7
IE2	Ensenada Trough	40-45	7.0
IE3	San Isidro Ridge	35-40	7.0
IE4	San Isidro Rift Valley	20-25	6.7
IF	*San Isidro Basin*	75-80	7.3
IF1	San Isidro Basin	45-50	7.1
IF2	Collnett Rift Valley	30-35	6.9
IG	*San Quintin – Bahia Rosario*	105-110+	7.5
IG1	San Quintin Embayment	30-55	7.1
IG2	Punta Baja – Bahia Rosario	50-60	7.2

Table Ib. Major Fault Sections and Segments – San Diego Trough Fault System.
[Fault sections in *italics*; **ID** corresponds to Figure 1]

ID	Fault Name	Length (km)	M_{max}
II	**San Diego Trough Fault System**	>340	7.9
IIA	*East Santa Monica Basin*	45-50+	7.1
IIA1	San Pedro Basin	40-45	7.0
IIA2	Santa Cruz – Catalina Ridge	75-95	7.4
IIB	*Santa Catalina Island*	95-105+	7.5
IIB1	San Pedro Basin	65-70	7.2
IIB2	West End (Santa Catalina Island)	25-30	6.8
IIB3	Catalina Escarpment	70-80	7.3
IIC	*Gulf of Santa Catalina*	85-90	7.4
IIC1	San Pedro Basin	15-20	6.6
IIC2	Crespi Knoll	25-30	6.8
IIC3	Southeast Catalina Ridge	25-30	6.8
IID	*San Diego Trough*	100-150	7.6
IID1	North San Diego Trough	80-85	7.3
IID2	South San Diego Trough	55-60	7.2
IIE	*Descanso Plain*	25-30	6.8
IIE1	Shepard Fan	10-15	6.5
IIE2	Banda Fan	10-15	6.5
IIF	*Bahia Soledad*	40-45	7.0
IIF1	Bahia Soledad	40-45	7.0
IIG	*Punta Santo Tomas*	60-65	7.2
IIG1	South Branch, Agua Blanca	30-35	6.9
IIG2	Soledad Ridge	40-45	7.0
IIG3	Cabras Bank	20-25	6.7

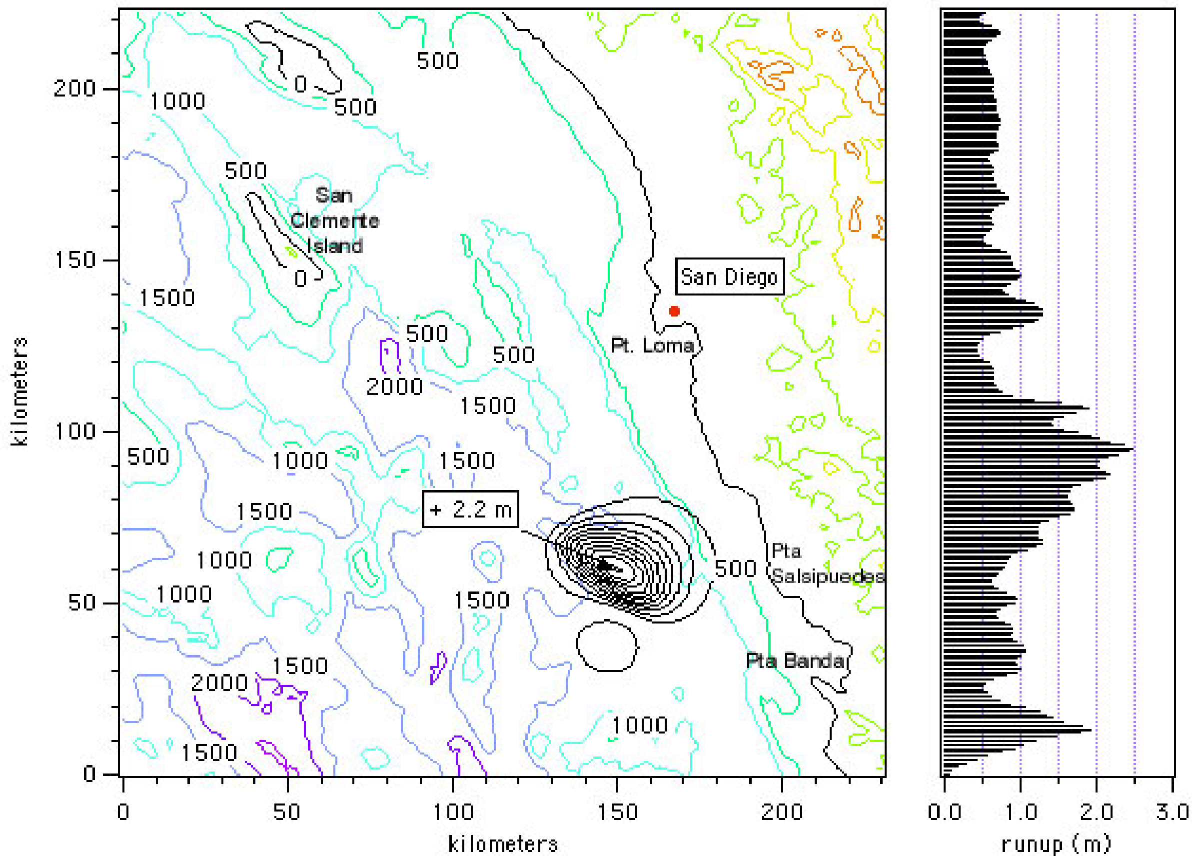

Figure 4. Location map and runup plot. The thick black lines are the seismic deformation contours (seafloor uplift) resulting from the simulated earthquake. The runup along the coast is plotted on the right.