

**Deformation History of a Major Restraining Bend along a
Right-Slip Fault:
The San Clemente Fault Offshore Northern Baja California, Mexico**

REPORT

The main focus of this project was to investigate the deformation history of a major restraining bend on the San Clemente fault. The San Clemente fault is a prominent northwest-trending, right-slip fault located in the California Continental Borderland. The fault extends more or less parallel to the shore with an average trend of 140 degrees west in the Pacific Ocean from southern California and northeast of San Clemente Island to northern Baja California, Mexico. The average strike in the bend region is 125 degrees oblique to the left. The location is approximately 75 km from downtown San Diego, California, and the restraining bend being studied occurs approximately 40 km south of the U.S.-Mexico border. The fault can be seen in the location map below in figure 1.

San Clemente fault

Figure 1: Location map of the San Clemente fault in relation to California and Baja California, Mexico.

The San Clemente fault is an active fault. By using the term “active,” it denotes that the fault is and has been moving in Quaternary time (Kasahara, 1981). The slip rate is about four to seven mm/yr with a maximum of ten mm/yr from several piercing points and the slip is in the right direction (Legg, 1985). There is evidence of this in the offset submarine channel by about five km, as seen in the seismic stratigraphy. Other evidence is seen in the migration of submarine fan sediments in the direction of the fault’s strike.

A strike-slip fault is a fault where the net slip is in the direction of the fault strike (Bates & Jackson, 1984). Of course, with many faults such as the San Andreas fault, there are bends or curvatures that break the monotony of the straight strike. Right-slip on a gently curved fault can result in oblique shortening and uplift within convexities of deformable plates and extension and sagging within concavities (Crowell, 1973). The San Clemente fault trace curves to the left creating an area of normal shortening. The restraining bend is an area of locked blocks that tend to push up the seafloor and create large earthquakes. The fault trace is also complex. There are at least five right-stepping en echelon fault segments that are accompanied by pull apart basins. There usually is extension at the ends of the fault where the blocks are pulling apart. The straight overall trend of the fault zone suggests that it is a high-angle, mostly vertical fault zone, even though individual fault dips are difficult to see with high-resolution seismic profiles, such as those used in studying the San Clemente fault in this research project.

The character and deformation history of specific fault zones such as the San

Clemente fault can be analyzed using interpretive techniques. In order to study the deformation history of the fault at its restraining bend, detailed maps of the seafloor along and adjacent to the fault were prepared using Sea Beam bathymetry data provided by the Scripps Institution of Oceanography and high resolution seismic reflection profiling surveys known as CFAULTS cruise number two, accomplished in September, 1979 (Legg, 1985). Faults can be mapped in three dimensions using closely-spaced seismic-reflection profiles. The character of offshore faulting can now be mapped with greater ease and with better detail than before, and the submarine features observed have less of an erosional influence than is seen on land.

A prominent layer of hemipelagic sediments (PEL), in a region on the seismic profiles that appears to be acoustically transparent, was mapped throughout the study. From the depth of those sediments respective to the seafloor, the age of the sediments were inferred by using a sedimentation rate for these draping sediments. The assumptions are that the rate of sedimentation is constant and is the same as other offshore hemipelagic sedimentation rates. From the following table, the age can be estimated to be between 200 ka and 660 ka, the best estimate about 470 ka.

Table for Computing Age of Prominent Acoustic Horizons (Legg, 1985)

East San Clemente Basin						
<u>Depth</u> (cm.)	Core 6P* ¹⁴ C Age (ka.)	<u>Rate</u> (cm/ka)	<u>Thickness</u> (sec)	Hemipelagic Layer		<u>Age</u> (ka.)
				<u>Thickness</u> (m-comp) ^{!!}	<u>Thickness</u> (m-unc)	
5-14	2.77 [†]		0.080	60.	84.	470±60
100-125	11.85±0.50	11±1				
190-210	14.00±0.90	48±12				
270-295	17.59±0.70	23±7				
				Banda Fan Poned Turbidites (Slope Deposits)		
			0.067	50.	70.	640±60
Average		18±2				

Formula for computing uncompacted thicknesses (after Moore, 1969; Hamilton, 1959)

$$H_o = H_f \frac{1 - n_f}{1 - n_o}$$

Where: H_o = uncompacted thickness of sediments
 H_f = compacted thickness of sediments (observed value)
 n_f = median value of porosity of compacted sediments
 (65% for clayey silts with 50-60 m Hf^{**})
 n_o = initial porosity of sediments (75% for clayey silts^{**})

*After Dunbar (1981)

[†]Robert Dunbar, personal communication

**After Moore (1969)

^{!!}An interval velocity of 1.5 km/sec (2-way) was used to compute the thicknesses at these shallow levels (Moore, 1969)

Table 1: Calculations of sedimentation rates and age of key horizons from piston core data (Legg, 1985).

Many things can be seen from seismic profiles. Below, profile B-13 is seen as figure 2.

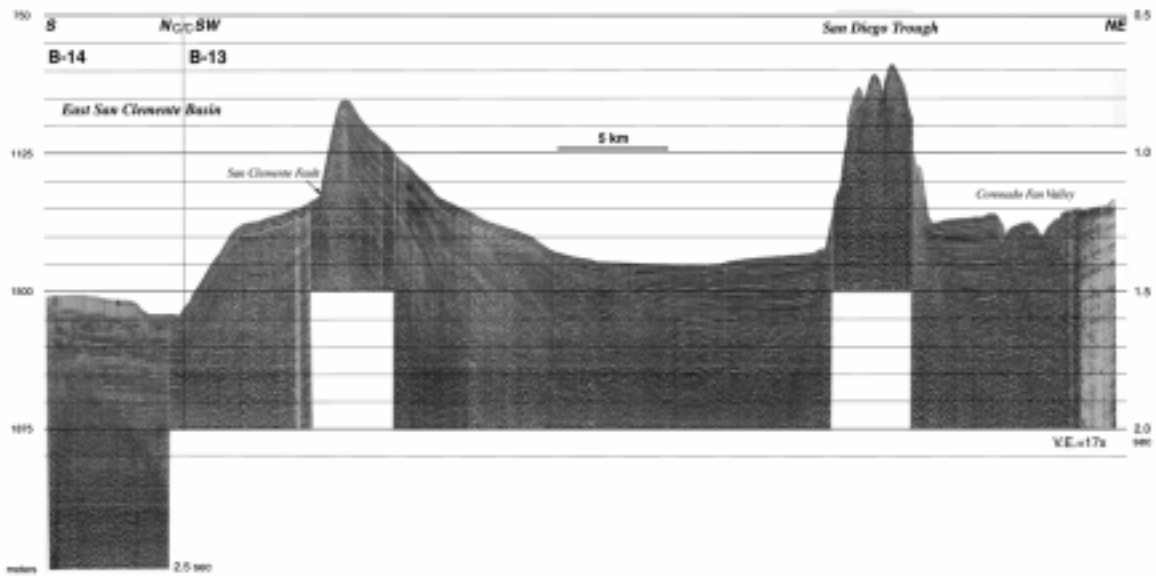


Figure 2: Seismic profiles B-13 and B-14 are from CFAULTS Cruise Two (Legg, 1985). The San Clemente fault and San Diego Trough are labeled.

In the following chart, three layers were mapped on each side of the fault. Because the uplift of the two bottom most layers are about equal, whereas the top layer shows less uplift implies that the uplift is within one to 1.5 million years young. Figure 3 is as follows:

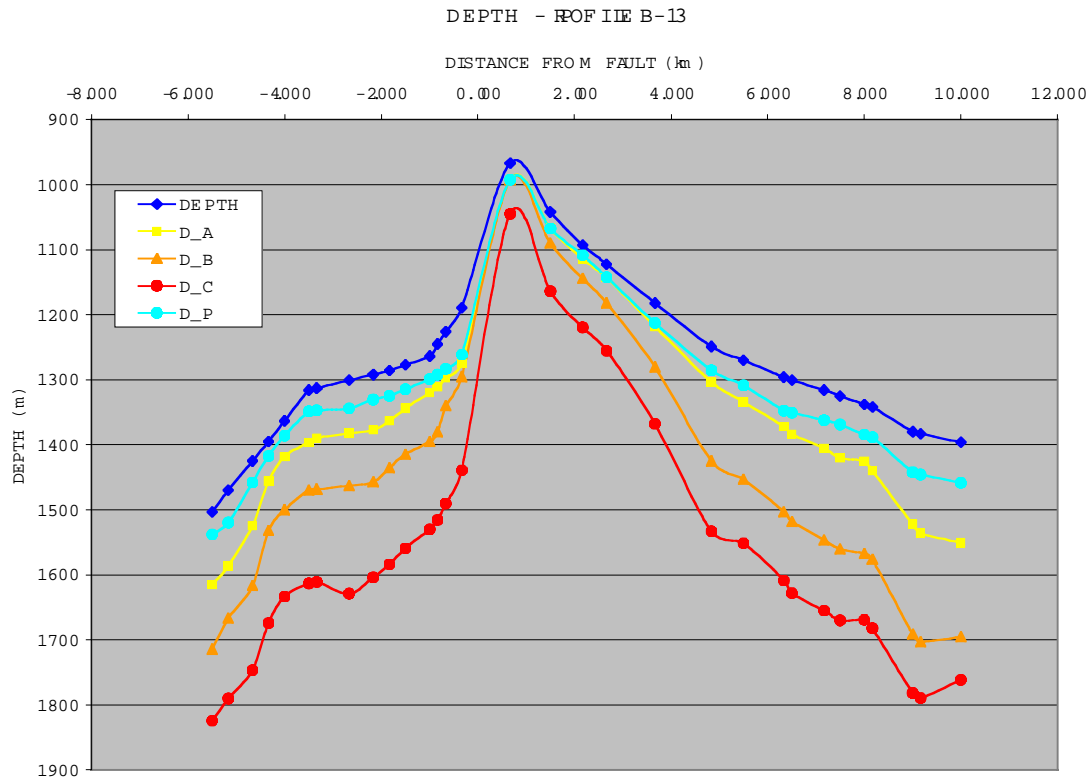


Figure 3: The depth of the seafloor is colored royal blue, the hemipelagic layer in aqua, and three chosen layers (yellow, orange and red) are mapped depth versus distance from fault. The profile is from line B-13 from CFAULTS cruise two (Legg, 1985).

The next chart reveals the relative uplift on the same profile B-13. What can be observed is the relatively large uplift on line B-13 reaches a maximum on the northeast side.

RELATIVEUPLIFT - PROFILE B-13

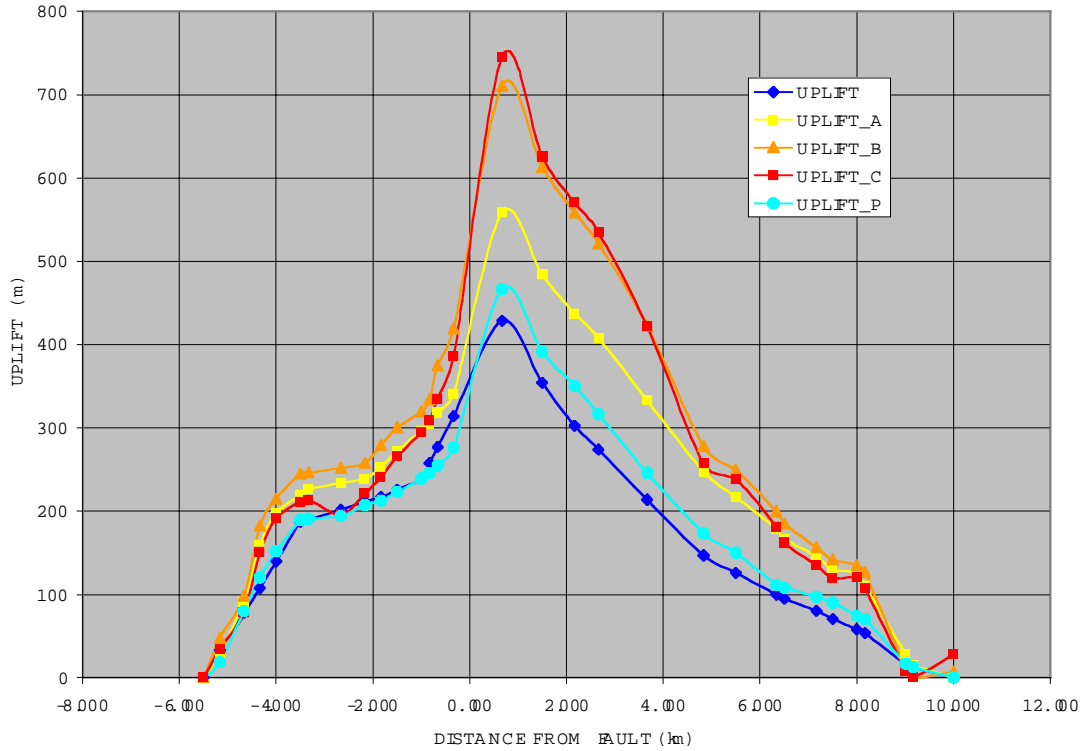


Figure 4: The relative uplift is graphed by depth versus distance from fault by using profile B-13 from CFAULTS Cruise Two (Legg, 1985).

From the data collected in 1979, an isopach map of the PEL layer was created. First of all, the top of the layer (TP) and bottom of the layer (BP) were determined through analysis of profiles. Values were taken and put into a data file for transport into a Geographic Information System program. Some address mapping was done and the difference between the TP and BP were mapped, creating an isopach map. the thinnest layers were discovered in the uplift areas of the northeast side of the bend where transpression exists, and thickest areas were observed in the southwest side where

transtension occurs. The uplift on both the TP and BP can be seen in figures 5 and 6.

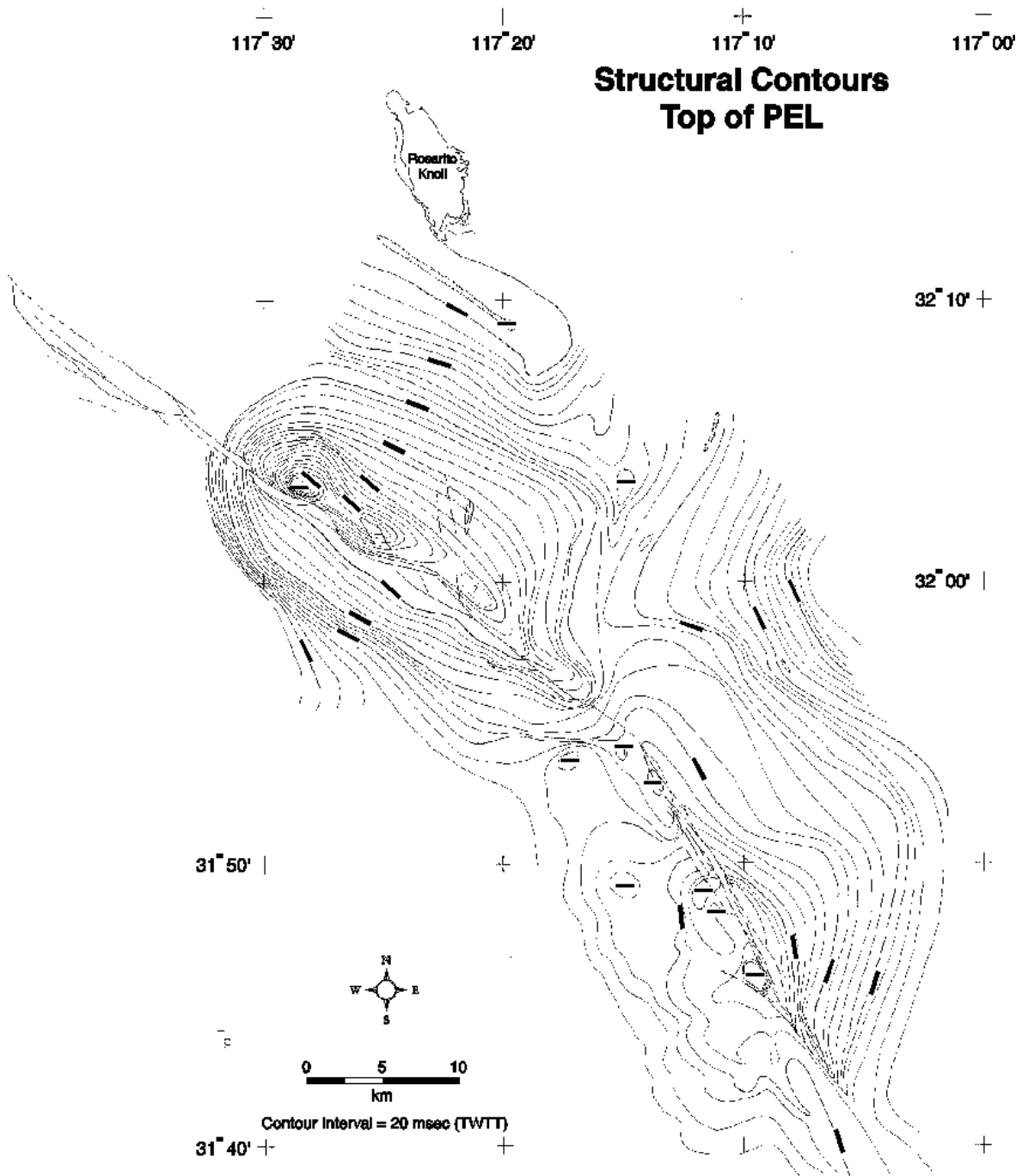


Figure 5: The TP, or the top of the hemipelagic layer, is contoured along the San Clemente fault here. The data comes from profiles on CFAULTS Cruise Two (Legg, 1985).

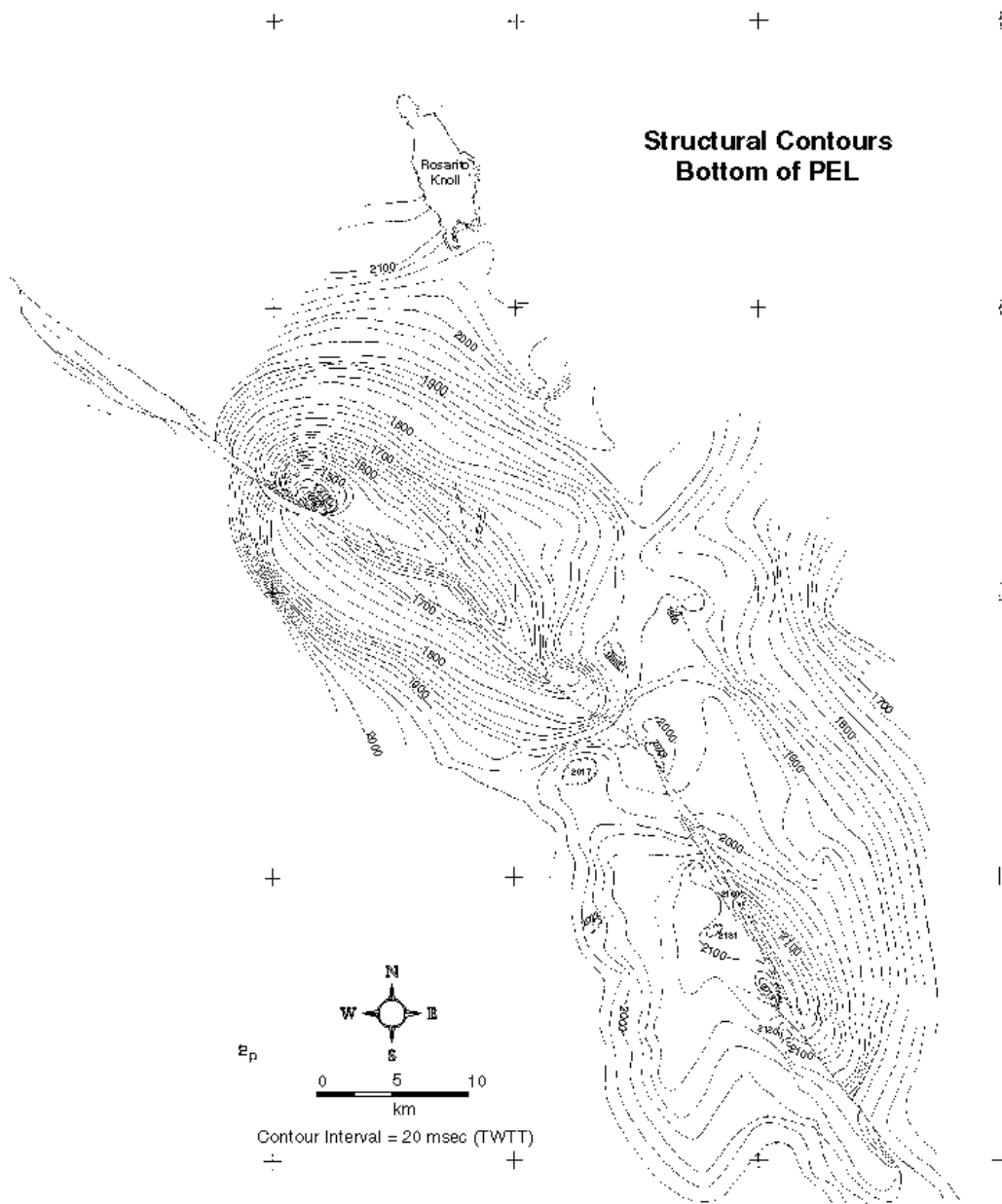


Figure 6: The BP, or the bottom of the hemipelagic layer, is contoured along the San Clemente fault here. The data comes from profiles on CFAULTS Cruise Two (Legg, 1985).

The San Clemente fault is the main influence in deformation, but other notable influences come from the Banda and Shepard fans on the east side of the fault.

Both seismic profiles and surface maps reveal seafloor deformation and disruption in layering due to faulting. Analysis and interpretation of the hemipelagic sediment layer profile indicated that uplift is shown by elevation contours and onlap of younger sediments on the flanks of the uplift. Thick layers of sediment in any given place implies the prior existence of a deep hole into which sediments ponded or progressive subsidence of the substrata accommodated successive increments of younger strata. The formation of either kind of sediment trap on a large scale requires pronounced vertical movements of the earth's crust" (Dickinson, 1974). In other words, to have these extensional holes being filled up into large amounts of sediments, fault vertical movement must influence the seafloor in order for those holes to be created.

The San Clemente fault is located within the transform plate boundary zone of the North American and Pacific plates. Because the "principal structural trend of the California Borderland is sub-parallel to the San Andreas fault system, the region is considered to be a part of the Pacific-North American (PAC-NOAM) tectonic boundary" (Legg, 1985). The California Continental Borderland area is a broad shear zone, formed by the fracturing of the northern end of a long, narrow Baja California microplate. The western boundary is the San Clemente fault, which shows mostly right-lateral faulting along a north 40 degree west trend, roughly parallel to PAC-NOAM relative plate motion (Legg, 1985, 1991).

The study of fault deformation history can provide valuable information regarding

the tectonic evolution of the larger plate boundary, especially since the transform plate boundary that is now the San Andreas fault was once on the San Clemente fault. It would be much easier for the San Isidro fault to step over to the San Diego Trough by a step to the San Clemente fault, but instead, a restraining bend was created because of an older, more important fault system. The results of this project can then be applied to other transform plate boundaries and strike-slip faults accompanied by restraining bends, such as the aforementioned San Andreas fault in California and the North Anatolian fault in Turkey.

The San Clemente-San Isidro fault zone is the largest offshore fault zone in the California Borderland, measuring over 400 km in length, and is one of the largest faults in the Pacific-North American region. Because of its size, the study of the San Clemente fault is important in its implication as an earthquake hazard, and particularly with its close proximity to the major ports of San Diego and Long Beach, a potential tsunami source. There is much evidence that even a moderate earthquake over 6.5 or larger or a landslide originated from steep escarpments created by the fault could trigger a tsunami that could cause widespread damage along a coastal southern California and Mexico. The San Clemente fault is also a strong ground shaking hazard that can be damaging to southern California and northern Baja California, Mexico. Even though the fault is not on land, the probability for a large, damaging earthquake exists and neighboring areas should prepare for the hazard that this fault will create.

California's changing landscape is continually being shaped by the tectonic forces related to the transform plate boundary. Any damage from earthquake activity on the San Clemente fault would be more extensive as the population of southern California continues

to grow, especially with much of this growth taking place near the coast where demand for homes is high. The same situation can apply elsewhere, since most of the world's population also resides within coastal regions where offshore faults are potential hazards. There are other regions in the world, such as those mentioned earlier, which have similar earthquake and tsunami hazard potential related to a sizable restraining bend in the fault. Information and data gathered from this study will help in understanding the components of earthquake faults, such as restraining bends, that lie within the plate boundary. Conclusions reached can assist other researchers on the characteristics of restraining bends within their respective faults by using the San Clemente fault as a case study.

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