**Geomorphology and Shallow Crustal Structure of Restraining Bends:
California Continental Borderland Examples**

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The mostly submarine California Continental Borderland provides exceptional examples of active and ancient restraining (and releasing) bend structures along major strike-slip fault zones. Erosional processes in the deep sea are greatly diminished compared to subaerial regions, thus allowing preservation of persistent oblique fault deformation in the seafloor morphology. Active deposition of turbidites and other marine sediments preserve a high-resolution geological record of the fault zone deformation and regional tectonic evolution. Multibeam swath bathymetry combined with high-resolution seismic reflection profiling provide us with detailed images of the seafloor morphology and shallow crustal geometry of these important strike-slip structures.

A 60-km long, 15-degree left bend in the dextral N40W-trending San Clemente fault provides an important basis for understanding restraining bend development. Here, varied structural styles and shallow crustal rheology are manifest in contrasting seafloor morphology. A southeastern area of uplift occurs in "soft" turbidite sediments and is expressed as a broad asymmetrical ridge including right-stepping en echelon anticlines and local pull-apart basins at minor releasing step-overs along the fault. The northeast uplift is narrow and more symmetrical, with steeper flanks consisting of more rigid sedimentary and possibly igneous or metamorphic basement rocks. Maximum bathymetric relief across the uplift ranges from 620 m to 660 m, whereas the structural relief observed in seismic reflection profiles exceeds 700 m. Seismic stratigraphic analysis shows that the uplift and transpression along this bend occurred within late Quaternary time, probably younger than about 1 Million years BP. North-trending branch and secondary faults show normal separation and displace the seafloor forming prominent grabens. Both the northwest and southeast sections of the San Clemente-San Isidro fault zone beyond the Bend Region are transtensional, forming an elongate pull-apart basin from Navy Fan to North San Clemente Basin, and a narrow turbidite-filled sag basin within the southern end of the San Diego Trough.

The 80-km long, 30-40 degree left bend in the submarine San Diego Trough - Catalina fault zone creates a large pop-up structure that emerges to form Santa Catalina Island. This ridge of igneous and metamorphic basement rocks has steep flanks and a classic "rhomboid" shape. A 7.5-km right step-over in the Catalina fault produces a prominent embayment along the southwest side of the uplift, forming an elevated pull-apart structure. The San Pedro Basin fault splits from the Catalina fault at the southeast end of the bend, shunting some right-slip around the restraining bend much like the Eastern California shear zone shunts some right-slip around the major San Andreas restraining bend of the modern Pacific-North America transform fault system. Also, the San Clemente fault merges with the Catalina fault at the southeast end of the Santa Cruz-Catalina Ridge forming a deep pull-apart basin remarkably similar to the intersection of the San Jacinto and San Andreas faults at near Cajon Pass between the San Gabriel and San Bernardino Mountains.

Development of major restraining bends offshore southern California appears to result from reactivation of major transform faults associated with middle Miocene oblique rifting during the evolution of the Pacific-North America plate boundary (Legg and Kamerling, 2004). Seismicity offshore southern California demonstrates the active character of these major right-slip fault systems. Transpression along major restraining bends would tend to lock the fault such that accumulated tectonic strain is released during large earthquakes like the 1857 Fort Tejon earthquake of the southern San Andreas fault. Submersible dives along a 100-m high seafloor escarpment at the northeast end of the San Clemente fault Bend Region discovered individual scarps in turbidite muds as high as 2-3 m and more than 1 km in length. These scarps appear to represent large paleoearthquakes along the San Clemente fault, with magnitudes comparable to recent historical events such as the 1999 Hector Mine (M7.1) and 1992 Landers (M7.4) earthquakes in the Mojave Desert. The overall length of these major offshore restraining bends and broad areas of seafloor uplift further pose a serious threat of locally-generated tsunami during such large submarine earthquakes.