Analysis of Fault-Fold Structures along the Newport-Inglewood Rose Canyon Fault System at an unprecedented scale using 3D P-Cable Seismic Reflection Data

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AGU 2018 Fall Annual Meeting

Abstract

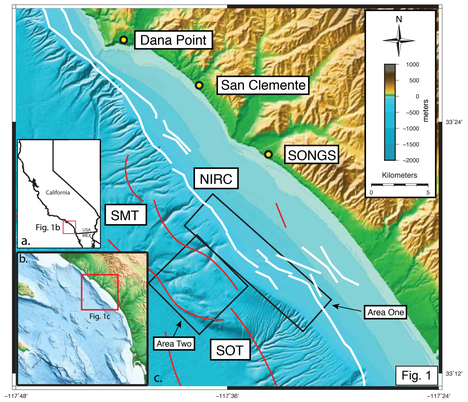
The Inner California Borderlands (ICB) is situated off the coast of southern California and northern Baja. The structural and geomorphic characteristics of the area record a middle Oligocene transition from subduction to microplate capture along the California coast. Marine stratigraphic evidence shows large-scale extension and rotation overprinted by modern strike-slip deformation. Geodetic and geologic observations indicate that approximately 6-8 mm/yr of Pacific-North American relative plate motion is accommodated by offshore strike-slip faulting in the ICB.

The farthest inshore fault system, the Newport-Inglewood Rose Canyon (NIRC) fault complex is a dextral strike-slip system that extends primarily offshore approximately 120 km from San Diego to the San Joaquin Hills near Newport Beach, California. Based on trenching and well data, the NIRC fault system Holocene slip rate is 1.5-2.0 mm/yr to the south and 0.5-1.0 mm/yr along its northern extent. An earthquake rupturing the entire length of the system could produce an Mw 7.0 earthquake or larger.

West of the main segments of the NIRC fault complex is the San Onofre Fault Trend (SOT), and San Mateo Fault Trend (SMT) along the continental slope. Previous work concluded that these are part of a strike-slip system that eventually merges with the NIRC complex. Others have interpreted these systems as deformation associated with the Oceanside Blind Thrust Fault (OBT) purported to underlie most of the region.

In late 2013, we acquired the first high-resolution 3D P-Cable seismic surveys (3.125 m bin resolution) of the San Onofre Trend as part of the Southern California Regional Fault Mapping project aboard the *R/V New Horizon*. Analysis of this data volume provides important new insights and constraints on the fault segmentation and transfer of deformation. Based on the new 3D sparker seismic data, our preferred interpretation for the San Onofre fault trend is a set of transpressional features associated with a shear zone and right lateral fault strands splaying off the NIRC fault. Such a scenario also is consistent with observations from the 3D volume along the shelf and upper slope that images westward stepping faults splaying off the NIRC system.

ICB and Survey Area



(Figure 1) (a) Regional map of California showing approximate location of Inner California Borderlands (ICB) in red square. **(b)** Area topography and bathymetry map of ICB showing approximate location of San Onofre coast and survey areas in red square. **(c)** High-resolution (25 m) bathymetry illustrating location of 3D seismic survey areas on continental margin relative to several southern California communities and San Onofre Nuclear Generating Station (SONGS).

Methodology

Our 3D data volume was acquired using a "P-Cable" system consisting of fourteen 50 m long streamers, spaced 6.25 m apart, with 8 embedded hydrophones each.

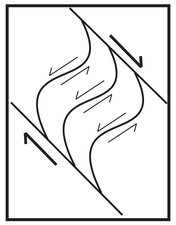
Data was collected in a ~45 km² survey area over the continental slope (230-700 m depths) using a single "sparker" seismic source (6.25 m shot interval) with a 2000 ms record length and 0.5 ms sample rate. Faults were picked with a pick spacing of 25 lines.

(Left) P-Cable rig attached to *R/V New Horizon* while underway off the coast of San Onofre, California, Oct. 2013. GPS was collected on the seismic source, and at various tow points on the rig.

Discussion

After fault mapping and analysis, we observe a number of highly segmented faults that we can separate into three different trends based on azimuth.

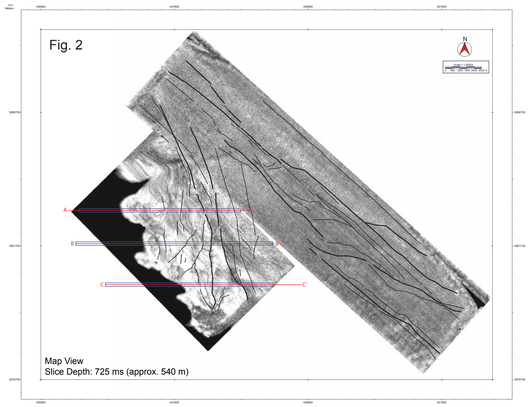
North-south trending faults appear throughout the volume but offset becomes smaller and more fragmented as we move westward down the continental slope. We do not observe lateral offset on these fault segments, instead there is accommodation made towards the top suggesting these faults have a trans-tensional component. These fault segments appear to be the largest in the volume and can be seen to bound deformation to the west. This deformation is moved further westward as these faults run northwards and eventually link up with segments of NIRC **(see transects in figures 3, 4, and 5)**. For further discussion and detail on the deformation observed in this volume, **please see Hector Perea's talk on Tuesday at 8:15 am (T21C-02)**.

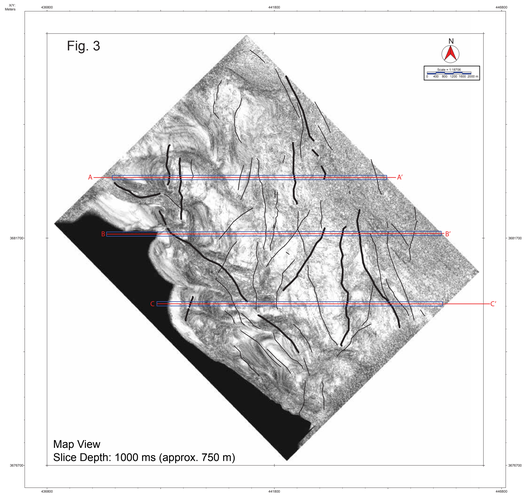


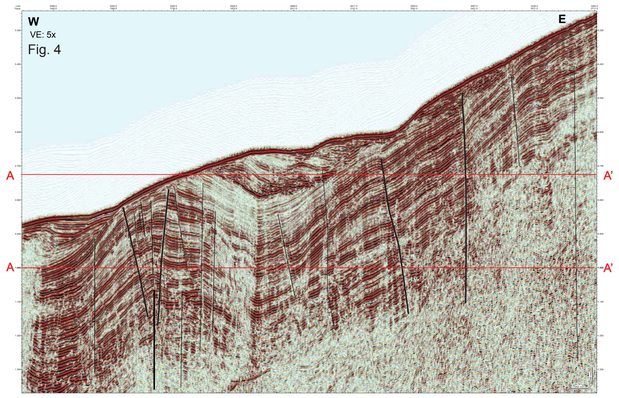
(Above) Schematic showing two right-lateral fault segments bounding a set of three left-lateral rotational "bookshelf" faults. These faults accomodate rotational stress in the shear zone between the two bounding faults. Based on our analysis of the 3D data in the San Onofre Trend fault zone, our hypothesis is that a similar kinematic model can explain our observations.

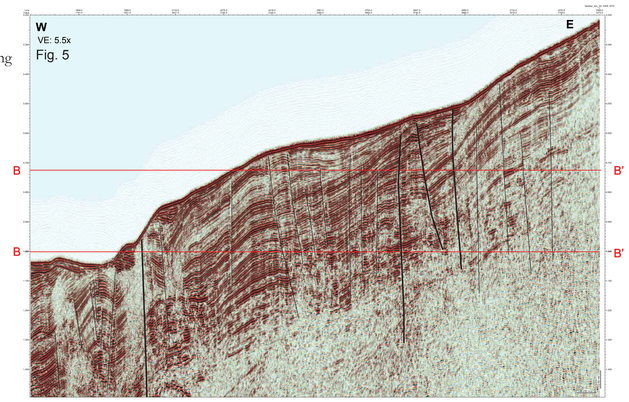
We observe a few large faults trending from northwest to the southeast, parallel to large segments of NIRC on the shelf. These faults occur at the base of the continental slope, therefore they aren't well-imaged in the 725 ms time slice **(figure 1)**, but can be viewed in the southeast of the 1000 ms time slice **(figure 2)**.

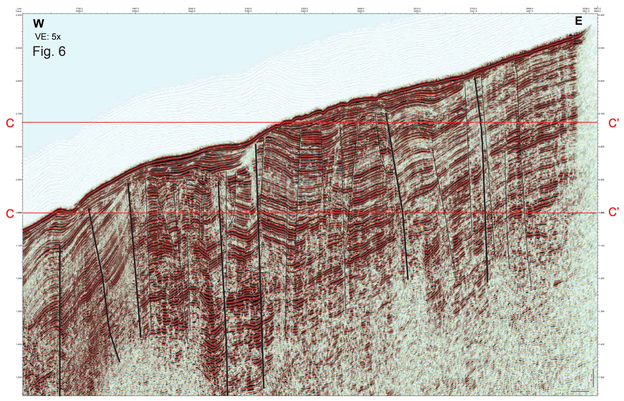
Finally we observe a number of small segments that occur northeast-southwest, orthogonal to NIRC. These segments show a certain amount of possible left-lateral offset. These segments are possibly rotated with the deformation **(see figure left)** and in some cases we observe linkage between these faults and the large north-south trending segments.











(Figure 2) Time slice at 725 ms of both 3D volumes displayed using similarity seismic attribute to enhance and provide ease of identification of discontinuities. Faults are shown in black. Line thickness denotes large faults. Red transects A-A', B-B', and C-C' correspond with vertical profiles in Figures 4, 5, & 6 respectively. Blue boxes around transect lines shows limit of view in vertical section. Not all minor faults mapped in the vertical sections are shown here.

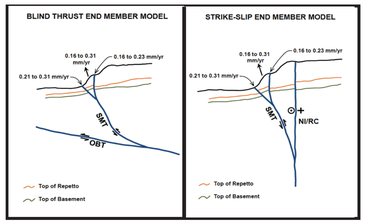
(Figure 3) Time slice at 1000 ms of only Survey Area Two 3D volume. Faults are shown in black. Line thickness denotes large faults. Red lines indicate transects shown in Figures 4, 5, & 6 respectively. Blue boxes around transect lines show limit of view in the vertical section.

(Figure 4) Vertical section showing transect from A-A' as shown in figures 1 & 2. Mapped faults displayed in black. Line thickness denotes large faults. Large faults that create the most deformation can be seen in the westernmost segments. Several large faults to the east step westward towards the Newport-Inglewood Rose Canyon system.

(Figure 5) Vertical section showing transect from B-B' as shown in figures 1 & 2. Mapped faults displayed in black. Line thickness denotes large faults. Major northwest-southeast trending fault segments near the base of the continental slope distribute strain into the shear zone system in the slope and shelf edge.

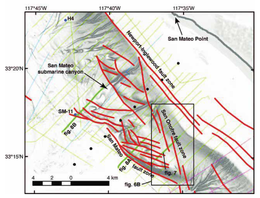
(Figure 6) Vertical section showing transect from C-C' as shown in figures 1 & 2. Mapped faults displayed in black. Line thickness denotes large faults. Large faults delimit the vertical section into three zones of deformation. Gentle stratigraphy to the east is the limb of a large antiform structure buried underneath shelf sediments. As the transect moves northwards, large faults bounding the areas of greatest deformation step westward.

Current End-Member Models



There are two end-member models to explain kinematics in this region. A blind thrust end-member model **(left above)** suggests that large fault zones such as the San Onofre Trend and San Mateo Trend terminate at depth into a low-angle Miocene-aged detachment fault that has been reactivated in the Pleistocene and Holocene. The presence of a blind thrust fault underlying much of the coastal margin represents a considerable seismic hazard for Southern California.

Our analysis of the 3D seismic data show deformation moving offshore and to the north. We observe predominantly transpression on faults in the northern and western part of the survey area with mostly strike-slip on the faults to the south and east. Therefore we prefer the strike-slip end-member model **(right above)**, where large faults join at depth with the larger Newport-Inglewood Rose Canyon system to the north.



(Left) Map of offshore San Onofre area, showing faults for Newport-Inglewood Rose Canyon, San Onofre Trend, and San Mateo Trend. Adapted from *Conrad, et al. 2018*.

The figure shows left-stepping segments in the San Onofre Fault Zone merging with the Newport-Inglewood Rose Canyon system.

Conclusions

Our goal when mapping this region was to gain some insight into the character and relationships of these different fault systems. We were especially interested in learning about structures related to interactions between NIRC and SOT/SMT. In support of that goal we acquired data over the continental shelf and slope off the coast of San Onofre State Beach where these fault systems interact. We then mapped approximately 300 separate fault segments and then characterized them based on deformation and extent.

Our observations of large fault segments distributing strain between NIRC and large, but immature segments at the base of the continental slope suggest that mapped segments of the SOT likely represent a shear zone accommodating rotation. Large bounding fault segments to the west are possibly decaying members of NIRC rather than a separate fault trend.

Our interpretations support the idea that the tectonics and geomorphology of this margin are controlled by strike-slip kinematics and thus fit the strike-slip end-member model more easily than a blind-thrust end-member model. For detailed analysis of deformation we observe in the volume, **please see Hector Perea's talk on Tuesday at 8:15 am (T21C-02)**.

Support for this project was provided by Southern California Edison (SCE).

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