NOTE: Based on Rentz (2010)
NOTES: (1) Based on Rentz (2010)
(2) Locations of seismic lines shown in Figure 8a
NOTES: (1) Top is from Kern & Rockwell (1992); Bottom is from Lajoie et al. (1992)
(2) Bottom presented in SCE (2001)
Shelf Break
• Correlates to last glacial maximum sea level low stand (~21-19 ka)
• Maintains uniform depth

Source: Grant and Shearer (2004)
LOCATION A

NOTES: (1) Modified from Grant and Shearer (2004)
(2) Locations of “A” and “B” shown in Figure A-11a

LOCATION B

NOTES: (1) Modified from Grant and Shearer (2004)
(2) Locations of “A” and “B” shown in Figure A-11a
1986 (M_L 5.3) Oceanside Earthquake Sequence

NOTE: Based on Ryan (2010, personal communication)
Conceptual model of basin inversion of a half-graben structure due to transpressional tectonics and wedging [modified after Bally, 1984]. (A) Development of the half-graben and associated rollover structure by normal slip on an extensional detachment (B) Basin inversion phase characterized by development of a hanging-wall wedge and asymmetrical contractional folds due to the reactivation of the extensional detachment.

Seismic examples of basin inversion structures associated with activity of the Oceanside Thrust. **(A)** Half–thrust reactivation along a lateral ramp of the Oceanside Thrust. **(B)** Tip–fold structure developed by contractional reactivation of the Carlsbad fault, which is located within the hanging wall block of the Oceanside Thrust. In both cases divergent termination of the seismic reflections within the Monterey Fm. define the stratigraphic expansion of the syn–rift sequence. Similarly, the phase of basin inversion is well recorded by the contractional geometry, internal onlap terminations, and general thinning of the syn–contractional Pico Fm. on the crest of the anticlines. **Inset:** Conceptual model of basin inversion after Bally [1984] and Letouzey [1990]. **(a)** Development of the extensional half–graben and associated rollover structure, **(b)** Period of quiescence and sedimentation of the post–rift sediments, **(c)** Reactivation of the normal fault with development of asymmetrical contractional fold. The model highlights the stratigraphic relationships between the three main tectonosequences characteristics of basin inversion. Location of the seismic lines is shown in Figure 3.5.
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SEISMIC HAZARD ASSESSMENT PROGRAM

SEISMIC REFLECTION PROFILE AND INTERPRETATION
OF THE FOLD AND THRUST BELT SOUTH OF LASUEN KNOLL
FROM RIVERO (2004)

FIGURE A-18
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SEISMIC REFLECTION PROFILE AND INTERPRETATION

FIGURE A-20
Diagramatic representation of the main structural elements and trends observed along transects X-X', Y-Y', and Z-Z'. The representation illustrates the lateral continuity of the offshore-dipping monocline, and the role of the Oceanside thrust as a regional basal detachment level. The diagram also highlights the complex arrangements of the modern contractual trends within the active submarine fold–thrust belt, and the control induced by the Miocene normal fault system and the propagating structural wedge in their location. A common pitfall in structural interpretation is also evident, the most important fold structure in a profile do not necessarily correlates across the trends (i.e. observed the transition of the San Mateo and San Onofre anticlines between profiles 2 and 3). Several basement riders located on top of the Oceanside thrust have been indentified based on local seismic expression. Some geometries have been simplified for clarity. The presence of the Newport-Inglewood strike-slip fault is inferred as restricted to the monocline location on Plate 3. Some modest amounts of dextral movement in the contractual trends is compatible with the interpretation and cannot be completely ruled out.

Modified from Rivero (2004)
SCHEMATIC DIAGRAM RELATING THE INNER CALIFORNIA BLIND THRUST SYSTEM TO THE SAN JOAQUIN HILLS

Computed contractional slip on the Oceanside Thrust derived using the excess-area method discussed in Appendix B. Dashed lines represent maximum and minimum values yielded by the method, when accounting for uncertainties on the geometry of the Oceanside Thrust, and on the depth-conversion process. Fault slip measurements derived from balanced structural interpretations (Plates 1 to 3, and Figure 3.11), and slip estimates derived from GPS analysis [Kier and Mueller, 1999] are also shown.

**SEISMOGENIC AREAS**
- Segment I: 1,242.0 km²
- Segment II: 1,921.3 km²
- Total Area (Segment I + II): 3,163.5 km²
Plot of maximum slip rates for the OBT from Rivero (2004)

- Since Venturian times (ca. 1.8 My)
- Since Repettian times (ca. 2.4 My)
SAN ONOFRE NUCLEAR GENERATING STATION
SEISMIC HAZARD ASSESSMENT PROGRAM

SCHEMATIC DIAGRAM SHOWING POSSIBLE STRUCTURAL CONFIGURATION OF ACTIVE OBT AND ACTIVE NI/RC FAULTS

Source: Astiz and Shearer (2000)
INTRODUCTION

The following references were considered in determining the weights for the end-member models discussed in Section 2.4. These references, in whole or in part, address the seismotectonic setting of southern California and the Continental Borderlands. Specifically, these authors offer information bearing on the structural, seismologic, paleoseismic, geomorphic, and/or geodetic character of the region. For convenience, the annotated bibliographies are subdivided into these same character categories.

ANNOTATED BIBLIOGRAPHIES


STRUCTURAL

- First suggested possible offshore extension of Holocene active traces of the Rose Canyon Fault Zone based on “a net of subbottom acoustic profiles spaced about 5 km apart.” The survey completed by the USGS and Scripps Institution extending from La Jolla into Camp Pendleton (up to latitude 33° 20’).
- Pointed out that straight sections are relatively narrow (0.5 km wide) with wider reaches “as much as 2 km wide at curves.”
- Indicated that “…Cretaceous and Tertiary sedimentary rocks that are generally nearly flat lying but dip moderately to steeply within and near the fault zone…”
- “The greatest local uplift lies adjacent to an S-shaped bend in the Rose Canyon fault…”
- “This uplift is believed to have resulted from compression there as a consequence of right-lateral strike-slip movement along the fault.”
- Further stated that “Corey (1954) and the other previously cited investigations that extrapolated the Rose Canyon fault to the northwest connected it with the Newport-Inglewood fault zone, near which the 1933 Long Beach earthquake of magnitude 6.3 occurred. The offshore evidence of the present study agrees with such a projection, at least as far north as Camp Pendleton.”


STRUCTURAL

- Marine terraces near SONGS "do not appear to be deformed or tilted."

SEISMOLOGY
- Shows focal mechanism solutions for 37 earthquakes along and near the onshore portion of the NI in Los Angeles and Orange Counties. Seventy-eight percent (78%) of these solutions are predominately strike-slip events; most of these are located along the main trace of the fault. The reverse or thrust events are mostly situated northeast or southwest of the main trace, most pronounced being along the Compton-Los Alamitos Fault to the northeast, but parallel to the trend of the NI.


STRUCTURAL
- “We used new (1989) digitally processed seismic reflection data with an average spacing of 1.5 km, in conjunction with older digital data and a grid of closely spaced, high resolution analog profiles, to map the geology of the inner margin.” Three major fault segments of the offshore NI/RC zone between Newport Beach and La Jolla and their geology are described
- Dana Point segment between Newport Beach and Las Pulgas Canyon is 43 km long, Oceanside segment between Las Pulgas Canyon and Encinitas is 32 km long, and Del Mar segment from Carlsbad to La Jolla is 34 km long.
- “Piercing points between Newport Beach and the correlative Cristianitos-San Onofre-Oceanside faults indicate that an average of 7 km of right-lateral displacement has occurred along the NIZ since early Pliocene time.”
- “Between San Mateo Point and Oceanside, multiple thrust faults and thrust generated folds or fault-propagation folds were mapped along the slope of the inner margin, west of the NI-RC fault zone...They may be separated into an inner thrust fault-fold complex that is probably a part of the flower structure of the NIZ, and an outer thrust-fold complex. The inner thrust fault complex is located near mid-slope, about at the 500 m isobath while the outer thrust complex follows the base of the slope near the 700 m isobath.”
- The main thrust fault of the inner thrust-fold complex is between 3 and 4 km beyond the shelf-break and dips 20-30 degrees east.
- “The main thrust of the outer thrust-fold complex trends southeast along the base of the slope of the inner margin. It is southwest-vergent and dips about 9 degrees east shoreward of the thrust ramp.”
- “At this time, a most probable slip rate of 1 mm/yr for the NI-RC zone is suggested.”
- “At this time, it appears that the most probable horizontal slip rate for the NI-RC zone is between 1.3 mm/yr and 2.1 mm/yr. If the Quaternary slip rates are emphasized the most probable modern (?) slip rate is between 0.8 and 1.3 mm/yr, or about 1 mm/yr.”
- “The thrust faults along the inner margin are active, as is evidenced by their surficial topographic expression and the displacement of Quaternary reflectors.”
“A potential seismic hazard, that has not been considered along the inner margin south of Dana Point, is posed by the thrust faults mapped off San Mateo Point-San Onofre to Oceanside and possible south to Encinitas.”

SEISMOLOGY

“The focal mechanisms are in general agreement with right-lateral, strike-slip faulting along the northwest trending NI-RC zone.”


STRUCTURAL

“The existence of a small normal component in the mechanism and in the geological cross sections suggests that the southwestern block of the Los Angeles basin is still subsiding.”

Recent data suggests that “most geological structures adjacent to the NIF are not secondary features resulting from wrench faulting (Wright, 1990 [sic]) but are rather primary structures resulting from north-south compression of the basin (Hauksson, 1990).”

“Absence of a thrust component is consistent with the slip partitioning model of the seismotectonics of the Los Angeles basin by Hauksson (1990).”

In the slip partitioning model by Hauksson (1990), “strike-slip faulting on vertical faults and thrust faults on gently dipping faults replace a system of oblique faulting…[t]he almost pure strike-slip mechanism of the 1933 earthquake and the pure thrust mechanism for the 1987 (M_L=5.9) Whittier Narrows earthquake are consistent with this slip partitioning model.”

SEISMOLOGY

Relocated 1933 (M_w 6.4) mainshock “showed right-lateral motion along the NIF [Newport-Inglewood Fault] with a small normal component.”

The “centroidal depth [of the mainshock] was 10±2 km.”

The “best fitting focal mechanism shows right-lateral strike-slip motion with a minor normal component.”

“Both the focal mechanism of the 1933 main shock and the spatial distribution of aftershocks indicate that the earthquake occurred on the NIF.”

Woodward-Clyde (1979) determined a different focal mechanism for the main shock based on first motion polarities and suggested the earthquake was not on the Newport-Inglewood Fault; this study by Hauksson is more accurate because it is based on fitting the whole teleseismic waveforms.

The “rupture initiated near the Huntington Beach–Newport Beach City boundary and extended unilaterally to the northwest to a distance of 13 to 16 km.”

“No reliable surface rupture was reported.”

“The main shock caused 85–120 cm of slip at depth.”

GEOPMORPHOLOGY

“Prominent surface expression [of the Newport-Inglewood Fault] may be a manifestation of the basement boundary rather than being primarily caused by the right-lateral offset,”
(i.e., metamorphic basement on the west juxtaposed against metaseds and volcanic on the east).


STRUCTURAL
- "[T]ranspressional structure along the offshore NI fault zone and prominent northwest-trending thrust faults at the base of the continental slope west of Newport and San Juan Capistrano suggest northeast-southwest convergence in this area."
- Post-Miocene north-south/northeast-southwest shortening in northern Borderland, extension or transtension on inner Borderland faults from latitude of San Diego southward.
- Palos Verdes Hills Fault is "recognized to have significant thrust or oblique-dextral reverse slip components."

SEISMOLOGY
- "[S]hortening in northeastern Borderland is manifested by the numerous earthquakes with reverse-faulting mechanisms."
- "[T]hrust-fault earthquake mechanisms have been observed as far south as the northern end of the San Diego trough."


STRUCTURAL
- “The Newport-Inglewood fault zone (NIFZ) is the best known structural feature of the Los Angeles basin (Figure 7).”
- “The zone has long been considered a classical example of the development of en echelon folds and faults along a deep-seated-strike-slip fault....”
- Numerous examples are provided of the dominance of Pliocene and later strike slip displacements and the significant variations in their corresponding vertical displacements.
- “Harding concluded that the structures within the zone “may be taken as a unit and related dynamically to one type of deformation – wrenching.”
- “There are dissenting views to this interpretation. Yeats (1973) found it satisfactory for the late Pliocene and Quaternary history of the Newport-Inglewood zone, but too simple for the late Miocene and early Pliocene. It does not account for the fact that most of the more diversely oriented normal and reverse faults (except for Inglewood oil field) became inactive during the Pliocene whereas the en echelon right-lateral slip faults of the Newport-Inglewood zone continued to be active through the Pleistocene.”
- “Each of the Neogene episodes has probably involved regional right-lateral simple shear, but along the NIFZ itself, total right-lateral slip since the middle Miocene has not exceeded 3km (Yeats, 1973) or about 1-2 mi. Evidence of this from the subsurface is compatible with the
estimate of 0.5 mm/year during the past 5 m.y. (Guptill and Heath, 1981) and 0.4-0.8 mm/year (Bird and Rosenstock, 1984).”

- “Classic wrench-fault deformation, however, is not the primary cause of most of the anticlinal features along the NIFZ. In the preceding discussion we have seen that many of these structures do not conform to a pattern of en echelon folding, but are related to local basement geometry and perhaps to a wide zone of pervasive shear within the basement. Along the southern NIFZ, the Long Beach, Seal Beach, and Huntington Beach (onshore) structures are block-edged force folds (Harding and Tuminas, 1988) forced along the middle to late Miocene block boundary. Offshore Huntington Beach has been constricted against the Offshore Newport ridge. Dominguez is a part of the El Segundo-Lawndale-Alondra fold trend, complicated by offset on the NIFZ. Inglewood (and perhaps Potero) formed in concert with uplift of the Las Cienegas block that buckled the sedimentary wedge against shallow basement of the western shelf (Wright, 1987d).”

- Although Hazenbush and Allen 1958 implied a 0.5mm/yr to 1.0mm/yr slip rate since mid-Miocene on the NIFZ in Huntington Beach, “detailed subsurface mapping of oil fields along the NIFZ has revealed a variety of structural patterns and histories, and many of these cannot easily be reconciled with a pure strike-slip origin.”

- “Faults within the San Andreas transform system may utilize relict zones of crustal weakness formed during earlier terrane accretion.”

- “In analyzing Pasadenaan deformation, the flake-tectonics model is more appropriate than the fold-and-thrust-belt model, although both models incorporate aseismic detachment at midcrustal depths. The flake-tectonics model is valid for all phases of Neogene deformation, both transtensional and transpressive, in the Los Angeles region.”

- “The transition between the strong compressive shortening of the Transverse Ranges and the moderate right slip of the Peninsular Ranges blocks occurs systematically across the Los Angeles basin. Those relationships… show contrasting structural styles on the two sides of the basin. The northeast flank is dominated by blind thrusts of the Transverse Ranges system that flatten with depth. The southwest flank features right-oblique faults of the Peninsular Ranges system that steepen into near-vertical zones of active seismicity.”; “Viewed south to north (GG’ to AA’), these cross sections confirm the gradual change from extension at the southern end of the basin to compressive shortening at the northern end….”

- “Relative motion between crustal flakes may involve rifting and separation, transform movement, or collision and shortening, combinations of these, and superposition of several modes over time. Local structures are shaped not by regional stress fields embracing areas hundreds of miles across but by the interaction of adjacent tectonic flakes, creating basement blocks and sedimentary wedges that may differ significantly in their densities, ductilities, and thermal characteristics.”; “In shaping local structure, the influence of these internal features of the shallow crust may be as important as the orientation of the stresses being applied.”

- “In forming a structure, the shape of the mold counts for as much as how the hammer is swung.”

- “All of those structures developed within a wide region of pervasive right slip associated with the evolving San Andreas transform zone. Nevertheless, strike-slip folding caused by displacement along an individual fault is not a dominant factor in the genesis of structures in the Los Angeles basin, though it may well have contributed to deformation along the
northern NIFZ (Figure 9) and perhaps the deformation along the Santa Monica fault (by left slip). That mechanism and other classic patterns of fold and fault development have been nullified by the effects of preexisting basement blocks and sedimentary wedges.”


**STRUCTURAL**

- Mapping of shorelines provides evidence for uniform uplift of the entire coastal zone in San Diego County (downtown San Diego to Oceanside) at a rate of 0.13 to 0.14 m/kyr during the Quaternary with exception of areas deformed locally by the Rose Canyon Fault Zone.
- Both higher and lower uplift rates are observed along the Rose Canyon Fault Zone, which is shown by its effects on shoreline configurations to have been active for at least the past million years.
- The average long-term uplift rate for the San Diego region is similar to those for other areas of coastal California that are dominated by strike-slip tectonics.

**GEOMORPHOLOGY**

- Shoreline angle elevations are estimated for 16 shorelines estimated to range in age from 80 ka to perhaps as old as 1.29 Ma.
- Shoreline geometry is modified both by regional uplift and by extensive faulting in the right-slip wrench system of the Rose Canyon Fault Zone.


**STRUCTURAL**

- “Rose Canyon fault appears to feed directly into the Newport-Inglewood fault zone to the northwest. Although the Coronado Bank fault may also feed slip into the Newport-Inglewood fault zone, the rate determined for the Rose Canyon fault in this study also provides a minimum slip rate for [the offshore NI/RC].”

**PALEOSEISMOLOGY**

- Rose Canyon Fault is Holocene active based on radiocarbon dates obtained from charcoal deposited stratigraphically below a tectonically offset channel.
- Authors demonstrate offset of channel is likely all or mostly tectonic with no or very minimal deflection.
- Minimum slip rate of the Rose Canyon Fault of ~1 mm/yr is afforded from the trenching, presuming 8.7 m of brittle slip in ~8150 years.
The “actual rate could be substantially higher if the age of the [tectonically offset] channel is as much as 1000 years younger than the age of [the radiocarbon date obtained from the charcoal].”

**GEOMORPHOLOGY**
- Rose Canyon Fault is late Pleistocene active based on a 17–28 ka terrace riser offset 33–35 m.
- Maximum slip rate of the Rose Canyon Fault of ~2 mm/yr is based on the maximum offset of the terrace riser (35 m) in the minimum amount of time (17 ka).


**STRUCTURAL**
- Propose large magnitude (>200 km) crustal extension formed LA Basin, Inner California Borderlands, and Southern California Borderlands in major late Cenozoic rifting.
- Several current right lateral strike slip structures originated as high-angle normal faults prior to Pliocene.
- “Faults such as the Newport-Inglewood and Whittier-Elsinore originated as high-angle, hanging-wall normal faults above detachments and hence, modern strike slip along these faults may end downward against the detachments.”
- Image detachment fault over regional extent, from “San Clemente to Oceanside.
- From San Clement to Oceanside, “30–50 km-long fold and thrust belt underlies the continental slope seaward of the Newport-Inglewood fault zone.”
- “[The] detachment fault has become reactivated in places and now accommodates northeast-southwest-directed contraction that has formed the overlying fold and thrust belt.”
- “Crustal shortening, which began in Pliocene time, appears to still be active.”
- “Thrust faults within this belt appear to be rooted into the former detachment, and crustal shortening has structurally inverted (uplifted and folded) a former sediment-filled trough situated along the Newport-Inglewood fault zone.”


**STRUCTURAL**
- “The California continental borderland structural province offshore of the southwestern United States and northwestern Mexico is nearly as wide as the Basin and Range province, but it is less well known....”
- “[P]late interactions are generally thought to have caused the borderland deformation, but the specific history and style of tectonism has been debated.”
- “Luyendyk et al. (1980) used paleomagnetic evidence to argue that the western Transverse Ranges had undergone 90°–105° of clockwise rotations, about vertical axes, mostly during middle to late Miocene time. Numerous way have been proposed to explain the clockwise
rotation and most of these link the rotation with large amounts of strike slip in the adjacent nonrotated regions to the north and south.”

- “The linked rotation–strike-slip models do not explain the most pronounced lithotectonic abnormality—the regional occurrence of the Catalina Schist that forms the basement of the inner continental borderland and the western part of the Los Angeles basin.”

- Other authors have suggested “that the Catalina Schist was exposed, from an undetermined depth, through a process of tectonic unroofing in a large inner continental borderland rift that developed behind the clockwise-rotating beam of the western Transverse Ranges.”

- “The Peninsular Ranges and Catalina Schist boundary has commonly been drawn at the near-vertical Newport-Inglewood and Rose Canyon fault system (e.g., Vedder, 1987). However, Crouch and Suppe (1993) described the boundary as a detachment-fault surface that dips gently to the east in the subsurface north of Oceanside. They used industry seismic-reflection data to support their view. Our data corroborate the findings of Crouch and Suppe’s (1993) in that the Newport-Inglewood and Rose Canyon fault system is entirely within sedimentary rocks of the Peninsular Ranges belt on line 120 (Fig. 6), and we imaged a similar deeply buried, low-angle fault having an east dip at about the same depth and position as Crouch and Suppe’s (1993) detachment fault. We think that the entire Peninsular Ranges–Catalina Schist boundary is along a low-angle detachment fault, which we call the Oceanside detachment fault.”

- “The Oceanside detachment fault is defined in the seismic data by several aligned, high-amplitude reflections with gentle apparent east.... These project eastward to an indistinct east-dipping reflection beneath the shelf...and they project westward and upward, through a zone of discontinuous, short reflections, to a series of east-dipping reflections...beneath the western part of the gulf.... We locate the breakaway zone of the detachment fault at the inclined reflections beneath the western part of the gulf.”

- “Numerous fault zones interrupt the coherency of the reflections that makes up the upper plate of the Oceanside detachment fault and some of these appear to disturb the sea floor.”

- “The Newport-Inglewood zone is inclined steeply east and it penetrates the entire reflective sequence, including the sea floor. The fault may have a strong normal component of offset. Most of the lesser steep faults appear either to merge downward with the detachment or they truncate at it. This could also be true of the Newport-Inglewood fault zone, although clear documentation is lacking in our data.”

- “Between the Gulf of Santa Catalina and the San Clemente Island region, there are several small fault-bounded and internally faulted basins....Much of the fill is probably syntectonic....It is not possible to determine the age of the basin fill.”

- “The San Clemente Island–Cortes Bank region is within the Nicolas forearc belt....Overall deformation within the Nicolas forearc belt is slight and most of the belt remains intact. There are numerous small structural basins, filled with middle Miocene and younger strata, that are bounded by young faults with pronounced normal separations, and these indicate that the belt was deformed by an episode of extensional and possibly strike-slip tectonism.”

- “The boundary between the Nicolas forearc and Catalina Schist belts is a prominent west-dipping fault...that has been called the East Santa Cruz basin fault.”

- “It is not possible to determine the magnitude and sense of slip from the seismic data, but the East Santa Cruz basin fault is assumed to have a large amount of right slip.... It probably also has incurred a large, but unknown, amount of normal displacement....The fault appears to break through to the surface....”
“The East Santa Cruz basin fault may splay into a group of west-dipping faults on north and west flanks of Sixtymile Bank...and between the East Cortes basin and the Blake Knolls.”

“The boundary between the Nicolas forearc and western Transverse Ranges belts is just south of the northern Channel Islands....Continuous reflectors...end abruptly at a steep fault that penetrates the seismic section to all depths. We call this the Channel Island fault zone.”

“The extensional basins, which serve to define the borderland structural province, formed during Miocene to Pliocene time.”

“Many of the largest basin-bounding faults...might still be active.”

“Most of the large northwest-oriented, basin-bounding faults exhibit characteristics that are consistent with a strong strike-slip component in addition to the large vertical separations that can be documented....They have long and straight fault traces and commonly have opposing down-thrown sides along the same fault trace....”

“We think that the Oceanside detachment fault...is the primary structure upon which the schist basement was uplifted relative to the Peninsular Ranges batholithic basement along the east side of the Catalina Schist belt.”

“We propose a two-stage model of upper crustal extension. The inner borderland rift formed during the early stage, beginning in early Miocene time when the western Transverse Range belt was oriented more or less north-south. The Catalina Schist was uplifted from middle crustal levels and exposed in the rift as the western Transverse Ranges began to rotate and the Nicolas forearc belt began to be displaced to the west. Most of the modern borderland physiography formed in the later stage, which began at the end of middle Miocene time. The later stage occurred in conjunction with the bulk of the rotation of the western Transverse Ranges. The later stage is primarily one of right-normal faulting in the borderland. Some parts of the borderland may still be in a right-normal slip regime.”

“[T]here has been approximately 100 km of extension across the part of the borderland...About 60 km of that extension took place during the early stage as the result of a migrating hinge of localized uplift and extension. About 40 km of extension occurred during the later stage as the result of distributed faulting on right-normal faults having northwest orientations.”

“We speculate that, after 15 Ma, the pattern of borderland deformation changed from localized extension (migrating hinge-flexural uplift model) to more distributed shear on right-normal slip on faults with north-northwest trends.”

“The Channel Island fault zone and the Santa Cruz Island and related faults, which also probably have curved traces...are viewed as left-slip zones that compensate for differences between the southwest end of the rotating western Transverse Ranges....”

SEISMOLOGY

“Patterns of seismicity (Legg, 1985) suggest that...the San Clemente, Coronado Bank, San Diego Trough, and Palos Verdes Hills faults, may be active.”

STRUCTURAL
- “Therefore, shortening must occur between 0.89 and 2.39 m/ka to achieve between 14±0.03 and 0.25±0.03 m/ka vertical uplift on a fault dipping 6-9 degrees. Using standard vector analysis we rotated the coordinate axes of the regional velocity field to calculate the component normal to the strike of the Oceanside fault as shown in figure 1 (SCEC Data Center, 1999). We then compare the regional surface velocity normal to the fault to the velocity required for current terrace uplift rates. This shows that the current surface shortening is within the range that would generate current uplift patterns but relies on the assumption that velocities at depth are consistent with surface velocities. The northern and southern terminations of the Oceanside fault are at approximately the San Joaquin Hills and the U.S. Mexican border respectively (John Shaw, work in progress).”
- “Of the three models tested in this project, uplift due to forebulging on a subsiding plate provides the best fit model for the observed uplift of marine terraces.”


STRUCTURAL
- “Indications of late Quaternary folding are present in the San Joaquin Hills at the southern margin of the Los Angeles basin.”
- “The San Joaquin Hills are the topographic expression of a northwest-trending anticlines between San Juan Capistrano and Huntington Mesa.”
- “Uplift of the San Joaquin Hills began in the early Pleistocene.”
- “Analysis of emergent marine terraces in the San Joaquin Hills...and ²³⁰Th dating of solitary corals from the lowest terraces reveal that the San Joaquin Hills have risen at a rate of 0.21–0.27 m/k.y. during the past 122 k.y.”
- “The location and thickness of Holocene sediments in the San Joaquin Hills suggest that tectonic uplift continued during the middle to late Holocene.”
- “[W]e do not have direct evidence for Holocene activity of the San Joaquin Hills thrust.”
- “A fault-bend fold model with movement on a northwest-vergent thrust fault best explains the elevations of marine terraces....”
- “In [one] interpretation the San Joaquin Hills thrust is a backthrust that soles into the Oceanside detachment (Bohannon and Geist, 1998) as part of a wedge-thrust structure.”
- “We prefer to interpret movement of the San Joaquin Hills blind thrust to be the product of partitioned strike slip and compressive shortening across the Newport-Inglewood fault zone.”
Bender, E.E., 2000, Late Quaternary uplift and earthquake potential of the San Joaquin Hills, southern Los Angeles basin, California – COMMENT: Geology, v. 28, no. 4, p. 383.

STRUCTURAL
  ▪ “Grant and et al. (1999) [sic] rather unequivocally demonstrated that the San Joaquin Hills...have risen at a rate of 0.021–0.027 mm/yr over the past 122 k.y. Based largely on geomorphic evidence, they attribute this uplift as a fault-bend fold above a southwest-dipping blind thrust fault.”
  ▪ Flower structures “have been shown to exist along the Newport-Inglewood fault zone (Harding, 1979; Wright, 1991), and the extensive, nearly vertical faulting observed in the San Joaquin Hills is suggestive of such a structure extending off of the fault zone.”
  ▪ “It appears more likely, on geologic grounds, to suggest that the uplift within the San Joaquin Hills is generated by squeezing upward along the Newport-Inglewood fault zone in shortening deformation accompanying northwest-southeast horizontal shear or transpression.”


STRUCTURAL
  ▪ “Bender’s conclusion that uplift within the San Joaquin Hills is generated by squeezing upward along the Newport-Inglewood fault zone by shortening that accompanies northwest-southeast horizontal shear (i.e., transpression) agrees with our statement that, ‘We prefer to interpret movement of the San Joaquin Hills blind thrust to be the product of partitioned strike-slip and compressive shortening across the southern Newport-Inglewood fault zone,’ (p. 1034, Grant et al., 1999).”
  ▪ “However, we disagree with Bender’s assertion that the structure of the San Joaquin Hills and proximity to the Newport-Inglewood fault make a blind thrust model unattractive.”
  ▪ The “San Andreas fault in central California [is described by Wilcox et al. (1973)] as an example of a wrench fault with a series of en echelon folds on the eastern side of the fault. These folds (anticlines) are now known to be underlain by seismogenic blind thrust faults (Stein and Yeats, 1989; Stein and Ekstrom, 1992) created by transpressive strain partitioned across western California (Lettis and Hanson, 1991). A similar structural relationship probably exists between the Newport-Inglewood fault zone and the San Joaquin Hills.”
  ▪ “Our data do provide strong evidence that the San Joaquin Hills are rising in response to a potentially seismogenic, underlying blind fault, and we suggest that this potential earthquake source should be included in regional seismic hazard models.”
**San Onofre Nuclear Generating Station**  
**Seismic Hazard Assessment Program**  
**2010 Probabilistic Seismic Hazard Analysis Report**


**Structural**
- Evidence in article forms the basis of several arguments regarding the location, geometry, and style of faulting in the offshore structural models.

**Seismology**
- “Fault geometries in this complex region [referring to offshore southern California] are often poorly constrained due to lack of surface observations and uncertainties in earthquake locations and focal mechanisms. To improve the accuracy of event locations in this area, we apply new location methods to 4312 offshore seismic events that occurred between 1981 and 1997 in seven different regions within the Borderland.”
- “Obtaining accurate locations for these events is difficult, due to the lack of nearby stations, the limited azimuthal coverage, and uncertainties in the velocity structure for this area.”
- “In general, our relocated events have small estimated relative location errors and the events are more clustered than the SCSN catalog locations”; “…under ideal conditions offshore events can be located to within 1 to 2 km of their true locations.”
- “Our final locations for most clusters are well correlated with known local tectonic features.”
- “We can relate the 1981 Santa Barbara Island (ML =5.3) earthquake with the Santa Cruz fault, the 13 July 1986 Oceanside (ML = 5.3) sequence with the San Diego Trough fault zone, and events near San Clemente Island with known trace of the San Clemente fault zone.”
- “Our locations define a northeast-dipping fault plane for the Oceanside sequence, but in cross-section the events are scattered over a broad zone (about 4 km thick)....This could either be an expression of fault complexity or location errors due to unaccounted for variations in the velocity structure.”
- “104 Events recorded between 1981 and 1997 that occur near Coronado Bank in the SCSN catalog, are relocated closer to the San Diego coast and suggest a shallow-angle, northeast-dipping fault plane at 10 to 15 km depth.”
- “We plot 65 events, those with standard errors less than 1.5 km.... Locations for events near the Coronado Bank region...occur at 10 to 15 km depth along an apparent northeast dipping fault close to the San Diego Coast.”
- “It is possible that these faults are shallow-angle thrust or detachment faults seen in seismic reflection data...to mark the boundary between the Peninsular Ranges to the east and the Catalina Schist best to the west”
- “If the Oceanside and/or Coronado events indeed occur on portions of a much larger system of offshore thrust faults, this would have important implications because it would establish that these faults are seismically active and a potential source of large future offshore events.”

STRUCTURAL
- Oblique convergent slip at depth may be partitioned separately onto NI/RC and OBT (model "D").
- "San Joaquin Hills are formed by northeast-vergent anticline that uplifts and defines marine terraces...[offshore imaging confirms] it formed above a shallow blind thrust [dipping ~23° southwest that is] restricted to the hangingwall of the [OBT]; at depth, we interpret that this shallow fault soles into the [OBT]."

SEISMOLOGY
- From seismology (i.e. 1986 Oceanside earthquakes), interpretation suggests Thirtymile Bank Thrust is through-going and not cut by San Diego Trough; if logic is extrapolated to OBT, then OBT is through-going and not cut by NI/RC Fault.
- "[R]elocated mainshock and aftershocks of [1986] Oceanside earthquake [are] clustered at ~8 km depth and [define] a 25-30° east-dipping surface" consistent with slip on Thirtymile Bank Thrust fault plane and an epicenter ~14-17 km east of San Diego Trough Fault.

GEOPMORPHOLOGY
- Imaged thrusts are "commonly associated with pronounced seafloor fold scarps."

GEODETIC
- Geodetic observations from Kier & Mueller (1999) indicate "as much as 2 mm/yr of NE-SW convergence between Catalina Island and the coast."


STRUCTURAL
- Geologically-derived fault slip and fold deformation rates may only be applicable when rate of deformation is constant over time.
- “[S]tratigraphic analysis of Quaternary deposits in [the LA Basin] show [the rate of] fold growth has not been constant during the last ~1 Ma.”
- “[C]onstant deformation should not be broadly presumed without specific supporting evidence.”

STRUCTURAL
- “Inner Continental Borderland blind-thrust system includes a pair of inverted Miocene extensional detachments...reactivated as low-angle thrust faults during the Pliocene.”
- “Thrust motions on these detachments produced several trends of contractional fault-related folds (e.g., San Mateo and Carlsbad structures) that partition oblique convergence with regional strike-slip systems.”

SEISMOLOGY
- “Earthquake hypocenters...suggest that the Inner California blind thrust system is active and seismogenic.”


STRUCTURAL
- Previous work by others suggests NIFZ and RCFZ connect along the continental shelf “with the main deformation occurring near the shelf edge.”
- “[O]bserve sediments at the seafloor deformed near the base of the slope at water depths of about 700 m on [multichannel seismic reflection] data between Dana Point and Oceanside.”
- Observe folding of seafloor between Oceanside and Carlsbad at 300 m depth.
- “[D]ata show recent faulting on the shelf (< 100 m water depth) associated with the Rose Canyon fault from Carlsbad to La Jolla.”
- “[I]nterpret the base of the slope faulting to be related to a strand of the NIFZ...that may connect with the RCFZ by a left step near Carlsbad, as evidenced by recent folding of the seafloor.”


STRUCTURAL
- Faults within the Coastal Fault Zone (>300 km in length) “appear to be kinematical linked.”
- “At a minimum, the Coastal Fault Zone extends from Beverly Hills, California (USA) southeast to the Punta Banda peninsula in Baja California (Mexico) and includes both [the] onshore and offshore...NIFZ (northern and southern segments), the offshore NIFZ, the Rose Canyon Fault, the Descanso strand of the offshore Coronado Bank Fault, and the Agua Blanca Fault.”
- “The offshore NIFZ is a structurally complex zone of folds and faults.”
“Continuity of the offshore and southern NIFZ was debated. Several studies (e.g., Barrows, 1974; Fischer and Mills, 1991) have concluded that they are continuous or kinematically linked, and therefore the offshore NIFZ is assumed to be seismogenic.”

“An upper bound slip rate of 3.5 m/yr has been estimated (Fischer, 1992) based on total offset with an estimated age of 2 Ma (Crouch and Bachman, 1989), but the Holocene slip rate is probably lower.”

“Fischer and Mills (1991) report a seismically active positive flower structure and thrust complex approximately 240 km long.”

“Several high-angle faults in the [San Joaquin Hills (SJH)] may be strands of the ancestral NIFZ (Bender, 2000) and show evidence of Quaternary surface rupture (Grant et al., 2000). Based on measurements of late Quaternary and Holocene uplift, the SJH have been interpreted to be underlain by an active blind thrust fault (Grant et al., 1999, 2000, 2002). Movement of the SJH blind fault may be kinematically linked to the NIFZ (Grant et al., 1999, 2000), the offshore Oceanside Fault (Rivero et al., 2000), or both.”

SEISMOLOGY

“Scattered seismicity occurs along the [NIFZ], although events are difficult to locate accurately due to poor station coverage.”

“The date of most recent rupture of the offshore NIFZ is not known [sic], although seismic-reflection observations and microseismicity indicate that it was during the Holocene.”

“Toppozada et al. (1981) estimated a M\(\geq\)6.5 [earthquake] and proposed a coastal or offshore location for the 1800 earthquake. If this interpretation is correct, the earthquake could have occurred on the offshore NIFZ.”

The onshore NIFZ northern and southern segments “have been seismically active during the historic period.”

“Despite relatively high historic levels of microseismicity, the northern NIFZ may be a seismic gap.”

“The recent seismicity suggest that the northern NIFZ might be in the latter stages of its seismic cycle.”

PALEOSEISMOLOGY

“[R]ecently published fault investigations in the northern Baja California peninsula (Mexico) and coastal southern California (USA) reveal evidence for geologically contemporaneous or sequential earthquakes along a >300-km-length, predominantly strike-slip seismic zone [which] includes structures previously mapped as the Agua Blanca, Rose Canyon, San Joaquin Hills, and southern Newport-Inglewood Fault zones.”

“The historic and paleoseismic records indicate that the Coastal Fault Zone has ruptures from the Agua Blanca to the southern NIFZ within the last few centuries, with the possible exception of the northern NIFZ and portions of the offshore NIFZ.”

“The date of the last surface rupture of the northern NIFZ is not known.”

“[T]he paleoseismic data and historic observations suggest that the northern NIFZ has not ruptured as recently as other sections of the Coastal Fault Zone.”

GEODETIC

“GPS measurements indicate that approximately 14% of the total Pacific-North America Plate motion occurs west of the Elsinore Fault, most likely distributed across the San
Clemente, Newport-Inglenook, Rose Canyon, and other coastal or offshore faults (Bennett et al., 1996).”

OTHER

- “Seismic hazard associated with [the Coastal Fault Zone] has been recognized for decades...but is still poorly quantified...due, in part, to the difficulty of integrating observations onshore and offshore.”
- “[T]he coastal faults have lower slip rates and longer recurrence intervals than many onshore faults and therefore are calculated to represent relatively low hazard...however, if we examine the entire zone, we find that it ruptured most recently in a temporal cluster or propagating sequence of large earthquakes. Therefore the hazard may be high if the sequence or cluster is still in progress.”
- “The southern California coastal fault zone [sic] might be in the later stages of [a] multicentury failure sequence.”


STRUCTURAL

- “The San Joaquin Hills...are the surficial expression of a faulted anticline parallel to the active Newport-Inglenook fault zone....”
- “Grant et al. (1999, 2000) proposed that uplift was generated by movement on an underlying blind thrust fault due to partitioned strike-slip and compressive shortening across the southern Newport-Inglenook fault zone.”
- Study of marsh deposits in Newport Bay, “a late Pleistocene erosional gap between the northern San Joaquin Hills and Newport Mesa.”
- Prior work by Stevenson (1954) suggested “the marsh bench was created by emergence of late Holocene marshland and subsequent death of the elevated marsh community. Stevenson (1954) hypothesized that ‘the greater height of the ‘marsh bench’ in the central area is probably the result of movement during Recent time of a major anticline and fault system which cut through the Bay in a NW–SE direction.’”
- “The pattern of uplift reported by Stevenson (1954) is consistent with both the geomorphic expression of the San Joaquin Hills and the expected vertical displacement field that would be generated by coseismic growth of the San Joaquin Hills.”
- “Our data agree with Stevenson’s (1954) hypothesis that the marsh bench emerged due to tectonic uplift of the San Joaquin Hills.”
- “The spatial pattern of emergent shorelines and marsh deposits roughly mimics the topographic expression of the San Joaquin Hills and is consistent with a tectonic origin.”
- “The marsh bench and coastal benches could not have formed solely by erosion or deposition due to a sea level highstand because the elevations are different at different locations and the average elevations are different on each side of Newport Bay and along the open coast. Therefore, the most plausible mechanism for creating both the marsh bench and coastal platforms is emergence by tectonic uplift.”
“The age of the marsh bench is constrained by radiocarbon dating.... Active marsh deposition and growth must have ceased on the marsh bench sometime after our samples were deposited.”

“Uplift of the San Joaquin Hills must have occurred after A.D. 1635, the earliest plausible age of the marsh bench.”

“Several fault models have been proposed to explain uplift and folding of the San Joaquin Hills. Grant et al. (1999) developed a model of a blind thrust fault dipping 30° to the southwest. Bender (2000) proposed that uplift is occurring in response to movement of the steeply dipping, strike-slip Newport–Inglewood fault system. Both types of faults may have contributed to uplift during the late Quaternary (Grant et al., 2000). A third model proposed by Rivero et al. (2000) attributes uplift to movement of a large regional thrust, the northeast-dipping Oceanside fault extending offshore of the San Joaquin Hills south to Oceanside and San Diego.”

“Several observations suggest that the San Joaquin Hills are underlain by a fault that is distinct from the NIFZ, although they may be linked kinematically.”

“Other topographically prominent anticlines, such as Signal Hill, are located within the structurally complex NIFZ and are associated with step-overs (Barrows, 1974). In contrast, the San Joaquin Hills anticline is east of the main NIFZ, and there is a releasing bend at the mouth of the Santa Ana River where the fault goes offshore (Morton and Miller, 1981) near the northern San Joaquin Hills.”

SEISMOLOGY

The 28 July 1769 historic earthquake is “a good candidate for the most recent earthquake that raised the San Joaquin Hills coastline.”

“Other candidates for the San Joaquin Hills earthquake occurred on 22 November 1800 and 10 July 1855.”

“There are no other documented earthquakes that could have generated more than 1 m uplift of the San Joaquin Hills after 1855, so we conclude that uplift and the causative earthquake occurred between A.D. 1635 and 1855.”

“Based on our interpretations of the data, this region was more seismically active in the preinstrumental period.”

GEOMORPHOLOGY

“In the San Joaquin Hills, wave erosion and coastal processes have formed a suite of shore platforms extending from the modern shoreline up to an elevation of greater than 300 m above sea level, indicating late Quaternary tectonic uplift.”

“[T]here is common agreement that modern and ancient shorelines are geomorphic indicators of sea level relative to land.”

“Along the open coast of the San Joaquin Hills, the lower emergent platform and shoreline are a few meters above the lowest (modern) wave-cut platform and several meters below any previously mapped or dated shoreline.... Based on position between the modern shoreline and dated shorelines at higher elevation, the lower emergent shoreline should be younger than 83 ka (stage 5a sea level highstand).... Therefore, the lowest emergent platform and shoreline...are most likely Holocene age (stage 1 sea level highstand).”

“Most emergent Holocene shorelines in tectonically active areas are less than 6000 yr old and reflect coseismic uplift rather than sea level fluctuation or large storms.”
“Changes in pollen types, as well as sedimentation, reported from a core of San Joaquin Marsh (Davis, 1992) are consistent with an interpretation of latest Holocene tectonic uplift of the San Joaquin Hills. San Joaquin Marsh is currently a freshwater marsh located between the city of Irvine and upper Newport Bay.... Radiocarbon dates and analysis of pollen from core sediments show that San Joaquin marsh responded to changes in relative sea level during the Holocene (Davis, 1992). After approximately 4500 yr B.P., freshwater pollen types were replaced with salt marsh types as marsh flora responded to the Holocene sea level highstand (Davis, 1992). Freshwater conditions returned briefly circa 3800, 2800, 2300, and after 560 yr. B.P.”

A “possible explanation is that tectonic uplift of the San Joaquin Hills elevated San Joaquin Marsh above sea level, causing a return to freshwater conditions.”


STRUCTURAL

- Structure of offshore NI/RC may be like onshore Newport-Inglewood Fault, with multiple strike-slip strands.

SEISMOLOGY

- Relocated two microearthquake clusters associated with offshore NI/RC: 1981 Oceanside cluster (19 events) and 2000 Newport Beach cluster (7 events).
- The “events [in the 1981 Oceanside cluster] align along a north-northwest trend about 0.5 km long...[and] define a nearly vertical plane between 12.5 and 13.0 km depth" and are "approximately parallel to the fault zone."
- The "strike, dip, and location of a plane fit by these events are consistent with active strike-slip faulting" on the offshore NI/RC Fault Zone.
- Composite waveform polarities "are consistent with a right-lateral strike-slip focal mechanism," but "cannot eliminate other possible focal mechanisms."
- "$[F]ive of seven events [in the 2000 Newport Beach cluster] are aligned in a pattern consistent with a shallow (7 km) north-northwest-striking, vertical or steeply dipping active fault," but polarities are too small for focal mechanism solutions.
- Overall, dataset too sparse to determine if there is (or is not) a through-going strike-slip fault zone.
- The “location and ~13 km depth of the Oceanside cluster suggests that the [OBT] is terminated by active strike-slip faults."

**STRUCTURAL**

- "Several of [the] contractional and extensional structures [offshore Dana Point] were previously interpreted as wrench-related thrusts and folds, and as 'flower structures' produced by active offshore segments of the Newport-Inglewood."
- "[I]nterpret most of the contractional trends sole into, and do not cross, the [OBT]."
- Complex faulting in basin inversions may be "prone to be confused with flower structure."
- "Shallow slip partitioning is the most likely description of the structural relationship between the Thirtymile Bank and San Diego Trough faults."
- "In many cases, seismic reflection data indicate previously interpreted strike-slip fault splays correspond with active hinges of contractional anticlines produced by...motion on a deep structural wedge."
- OBT Segment I (Dana Point to south of Carlsbad) slip rate 0.88–1.17 mm/yr; M 7.1 → return interval (RI) = 1070–1430 yrs; M 7.3 → RI = 1480–1960 yrs.
- OBT Segment II (south of Carlsbad to south of San Diego) slip rate 0.70–0.94 mm/yr; M 7.3 → RI = 1840–2470 yrs.
- OBT full length, M 7.5 → RI = 2030–3390 yrs.

**GEOMORPHOLOGY**

- "Local asymmetric anticlines with bathymetric expression, sitting on top of regional rollovers" are associated with mapped structures (proposed thrust systems).
- "Structural wedge system above the [OBT] shows a spatial correlation with the occurrence of Quaternary uplift in adjacent coastal areas," e.g. San Joaquin Hills, and marine terraces and strand lines along coastal Orange and San Diego Counties.


**STRUCTURAL**

- “The San Mateo anticline developed by the upward propagation of reverse slip during the inversion of Miocene half-grabens.”
- Oceanside detachment “is not folded by the contractual structures; thus we interpret that the San Mateo Anticline is formed by thrusting ramping up from this detachment surface.”
- San Mateo ramp is also folded by a younger, deeper thrust.
- San Mateo thrust and underlying thrust “terminate in structural wedges...that propagate slip back to the hinterland...as no foreland structures that could account for the transfer of slip exist beyond the San Mateo anticline.”
- “[I]nterpret the San Mateo Anticline as an imbricated fault-bend fold produced by the upward propagation of contractual slip from an inverted normal fault into multiple detachment levels.”
“The back-limb geometry...indicates the presence of a deeper structure [that] refolds the shallow thrust sheet of the San Mateo Anticline in a way consistent with a break-forward system.”

- Estimated total shortening offshore the San Clemente region is 2.5 km.
- “The San Mateo anticline is an imbricated fault-bend fold originated by basin inversion processes” along a thrust that “reactivated a segment of a northeast-dipping Miocene normal fault.”
- “The phase of basin inversion also reactivated a Miocene low-angle detachment as the [OBT]” and the OBT “transferred contractual slip to associated synthetic and antithetic normal structures, inverting a major graben-boundary fault, and generating a regional structural wedge [that] controls the location of a prominent monocline with bathymetric expression.”


**STRUCTURAL**

- A “restraining bend exists where the fault curves or steps to the left when following the fault trace. Crowding of crustal material by lateral movement into the fault bend produces uplift and crustal thickening....”
- “Right-slip on irregular fault traces in the California Continental Borderland “has produced numerous restraining bend pop-ups that exhibit distinctive seafloor morphology.”
- “The submarine basins of the Borderland range in depth from a few hundred metres to more than 2000 m...erosion is greatly diminished in these deep basins compared with subaerial regions, so that pop-up morphology is well preserved on the seafloor.”
- “The San Clemente fault zone includes a 60-km-long restraining bend that exhibits prominent seafloor uplift in the 1300-m deep Descanso Plain offshore of northwest Baja California....”
- San Clemente Fault bed region minimum uplift rate is 0.47 to 0.70 m/ka.
- “The Catalina Fault forms an 80-km-long restraining double bend (cf. Crowell 1974) between the Santa Cruz-Catalina Ridge and San Diego Trough fault zones. Uplift due to oblique convergence along this transpressional fault has produced Santa Catalina Island and the wide submerged shelf and slope surrounding the island.”
- Model for restraining bend evolution:
  - “First, the strike of the principal displacement zone (PDZ) in the major restraining bends is parallel to the Miocene Pacific-North America (PAC-NOAM) relative motion vector(s).”
  - “Second, the major faults within the restraining bend pop-up have very steep to vertical dips.”
  - “Third, the pop-up structures for the major restraining bends have structurally inverted Miocene basins.”
  - “Fourth, there is an overall right-stepping en echelon character to the major right-slip fault pattern of the Borderland.”

**STRUCTURAL**
- Parts of Carlsbad-Coronado fault system coincide with the SCEC CFM OBT.


**STRUCTURAL**
- Presents argument for the model that the elevated terraces along the Pacific coast of northern Baja California and southern California are the result of the distal effect of “flexture of the elastic lithosphere driven largely by heating and thinning of the upper mantle beneath the Gulf of California (and the Salton Trough) and eastern Peninsular Ranges.”
- “Pliocene strata deposited at sea level along the Pacific coastline in southern California have not been uplifted significantly above Quaternary marine terrace deposits.”


**STRUCTURAL**
- “A 3-D sequence-based structural/stratigraphic model for the Los Angeles Basin is being developed by the USGS for use in earthquake hazards and groundwater resources research.”
- “The Quaternary section reaches a maximum thickness of more than 1280 m in the Lynwood area east of the Newport-Inglewood (N-I) fault zone. In the west basin, the Quaternary section reaches its greatest thickness (>410 m) in San Pedro Bay just east of the Palos Verdes fault. Of the inter-basin structures that impact the Quaternary section, the Compton-Alamitos fault (Wright, 1991) is the most prominent. Discreet faulting of mid-late Pleistocene deposits and structural relief of up to 300 m is suggested by the seismic data and by anomalous water levels near Los Alamitos. West of the N-I fault, two W-NW-trending inter-basin faults offset mid-late Pleistocene sediments and may serve to consume slip from the N-I. The M4.7 Hawthorne earthquake of May 18, 2009 was located near the northernmost of these structures and has a fault-plane solution consistent with the geometry and kinematics of this fault as evidenced in the geology.”

STRUCTURAL
- Where the Rose Canyon FZ "is imaged on industry MCS records, [it] forms a complex flower structure near the shelf break" (offshore Encinitas).
- "[M]ain strand of [offshore] Newport-Inglewood FZ forms a prominent positive flower structure" (offshore San Onofre).
- NI/RC bend/connection "is accommodated by reverse faulting...faulting dies off rapidly [away from bend/connection], however folding continues [from] Carlsbad Canyon [to] near the left step [in] Newport-Inglewood FZ."
- "[I]ndustry seismic reflection profiles suggest the [OBT] might not be continuous," and it is "uncertain [whether OBT] offsets San Onofre FZ south of San Mateo Point."
- "[lack sufficient data] to determine whether or not [OBT] intersects and offsets Newport-Inglewood FZ."
- "[S]outh of La Jolla Fan Valley...little evidence for shortening associated with [OBT]."
- Of the main, through-going offshore faults, the "more northerly...tend to be transtensional and the more westerly [tend to be] transpressional."
- Key issue of San Mateo FZ and Carlsbad FZ: are these reverse faults "indicative of broad scale contraction...related to the reactivation of the Oceanside detachment as a blind thrust...or related to more localized complexities associated with slip partitioning along Newport-Inglewood FZ."
- "[U]plift of marine terraces along much of the coastline between Newport Beach and La Jolla provides possible evidence for the large-scale reactivation of the entire Oceanside detachment surface as a blind thrust"..."however, uplift of terraces could also be explained by transpression along Newport-Inglewood FZ."
- "[A]lthough a low-angle detachment surface is imaged...throughout much of the offshore Gulf of Santa Catalina, there is not unequivocal evidence that it has been reactivated as an uninterrupted active thrust fault."


STRUCTURAL
- The OBT "has little effect on the ~2.5 Ma horizon above [it], and a regional anticline expected due to deeper blind thrust slip beneath the Gulf of Santa Catalina is lacking."
- "Significant Plio-Quaternary folding is only present where the [OBT] bends to merge with the Carlsbad fault."
- Carlsbad Fault is oblique-right reverse, "SW-verging thrust slip [on it] contributes to uplifting continental shelf...and San Joaquin Hills."

**STRUCTURAL**
- "[R]ight lateral NI fault [is] part of a larger 3D system of oblique-right reverse faults."
- The central OBT does not deform early Quaternary seds and has "normal separation near [the] base of [the] Pliocene horizon."
- Northwest OBT coincides with San Mateo/Carlsbad Fault; progressive tilting in hangingwall forelimb indicates subsidence; Newport Beach/Oceanside slope and shelf and San Joaquin Hills being uplifted on San Mateo/Carlsbad Fault.
- Southeast OBT coincides with Coronado Bank Fault, locally pure right lateral.


**STRUCTURAL**
- Based on recent high resolution seismic and bathymetric surveys, the mapped traces of the Palos Verde, Coronado Bank, San Diego Trough, and San Pedro Faults have been significantly altered.
- Indicate that the Avalon Knoll Fault also shows evidence of recent offsets and “these faults are thought to accommodate about 5-8 mm/yr of slip .... but it is not clear how slip on these faults is distributed....”
- Re-defined the Catalina Fault as inactive and report the Catalina Island is subsiding rather than rising.
- Presented the USGS’s latest map of the NI/RC fault system, but do not discuss it specifically.
- The key value is the more accurate map of the San Diego Trough Fault and correlating this more location and mapped configuration with its associated step-overs and the 1986 Oceanside earthquake (See Ryan, 2010, personal communication).


**STRUCTURAL**
- Amplifying on Ponti, D.J. and Ehman, K.D. (2009), “At present, faults are highly simplified in the model; we have not accounted for every known structure in the basin, but instead have focused on modeling faults that have an apparent impact on groundwater flow... Vertical terminations of the faults have also not yet been tightly constrained.”

**SEISMOLOGY**
- “The Charnock fault, originally proposed by Poland and others (1959) to explain groundwater anomalies within Pleistocene sediment, may in fact correspond with a more
NW-trending structure identified by Wright (1991) that appears associated with a trend of seismicity evident in recent relocations. The M4.7 Inglewood earthquake of May 18, 2009 was located near the southern end of this seismicity trend and has a fault-plane solution consistent with the geometry and kinematics of this fault as evident in the geology.”


STRUCTURAL

- “We evaluate several different styles of geometric and kinematic interactions between high-angle strike-slip faults and the low-angle detachments, and favor interpretations where deep oblique slip is partitioned at shallow crustal levels into thrusting and right-lateral strike-slip faulting. “
- “Restored and Balanced cross-sections provide a minimum SW-directed slip of 2.2-2.7 km on the Oceanside Thrust, and illustrate the role of this detachment in controlling the process of basin inversion and the development of the overlying fold-and-thrust belt.”
- “Interpret observations to reflect a complex mixture of strike-slip and blind-thrust faulting in the Inner Borderlands that is similar to the style of deformation in the onshore LA basin.”
- “Miocene low-angle normal (detachment) faults... that were reactivated by basin inversion processes initiated in the Late Pliocene, during the onset of the modern transpressional regime.”
- “[N]ew geometric representations of the offshore Newport-Ingleswood, Rose Canyon, and San Diego Trough fault zones...consistent with basin inversion processes and the presence of both active blind-thrust and strike-slip faults in the southern Inner California Borderlands.”
- “[P]rovide insight into the subsurface geometries of complex zones where coeval active strike-slip and thrust faults interact. Both types of fault systems are deemed likely to be active, and should be considered in the context of regional earthquake hazards assessment.”
- “[M]otion on the Oceanside Thrust generated four prominent contractional fold trends. Three of these are foreland-directed structures (San Mateo, San Onofre, and Carlsbad Trends) that produce prominent fold scarps at the seafloor...suggesting Quaternary activity. The fourth is a backthrust (hinterland-directed) system...manifested in a laterally continuous monocline that controls the relief and bathymetric expression of the shelf.”
- “[C]ontractional and extensional structures represent local restraining and releasing bends along the offshore extension of the Rose Canyon strike-slip fault. At depth, the NI and RC strike-slip fault zones intersect with the Oceanside Thrust...at relatively shallow levels of~4km in the north and deeper ~10 km in the south. Data are insufficient to uniquely define the manner in which these two fault systems interact. Scenarios where the two fault systems interact at depth in a manner consistent with their coeval activity are favored.”

SEISMOLOGY

- “The Inner Borderlands do not display the apparent spatial correlation between EQ activity and regional strike-slip fault zones that is observed around the onshore region of the Peninsular Ranges...Seismicity in this area is diffuse and scattered.”
Rockwell, T., 2010, personal communication.

GEOPMORPHOLOGY

- 3-D trenching and “Paleoseismic work along the onshore Rose Canyon fault zone in the City of San Diego clearly demonstrates that the fault has sustained recurrent Holocene activity …”
- “Considering that the surface soil represents a long period of stability, it is not possible to simply space the timing of all six events equally for the past 9.3 ka. In fact, if the interpretation is correct that the surface soils represent at least 5 ka of development, then five of these events occurred as a cluster in the period between about 9.3 and 5 ka, with an average interval of recurrence of less than 1 ka.”
- “If the fault principally behaves in a clustered seismicity mode, and if the five early Holocene events represent such a cluster, then one must consider the possibility that the recent earthquake of ca. AD 1650 represents a return to activity and is possibly the first in the next cluster of large earthquakes.”


STRUCTURAL

- “Marine terraces on the southwest flank of the uplift (Kern, 1977; Kern and Rockwell, 1992), along with the presence of the Linda Vista Formation marine terrace alluvium capping Mount Soledad, attest to the higher rate of uplift of the restraining bend area (0.25 mm/yr) relative to the surrounding coastal plain (0.13 mm/yr) (Kern and Rockwell, 1992), with the background regional uplift attributed to rift-flank uplift from extension in the Gulf (Mueller et.al., 2009).”
- The combination of the releasing step plus a change in fault strike make the Oceanside step a likely (northern) termination zone for ruptures, although a through-going rupture cannot be precluded.”
- “However, the San Joaquin Hills may represent uplift associated with a step from the northern termination of the Rose Canyon to the Newport-Inglewood fault zone.”
- “If the Oceanside step-over is a barrier to rupture propagation, it would divide the Rose Canyon fault into two roughly similar-length sections: a 65 km segment from San Diego Bay to Oceanside, and a 55 km segment from Oceanside to the San Joaquin Hills…one cannot preclude rupture of the entire Rose Canyon fault for a distance of more than 100 km. However, I consider this model a lower likelihood than rupture of individual segments and weight it a 25%, versus 75%f for the more segmented rupture behavior.”

PALEOSEISMOLOGY

- The “most recent earthquake occurred sometime between AD 1523 and 1769. These 3-D trenching data further suggest that about 3 m of right lateral, strike-slip displacement occurred during this event, with a 1:10 ratio of vertical to horizontal displacement.”
“In particular, the onshore data supports the argument that the high-angle, right-lateral, strike-slip as NI/RC Fault System is a primary seismic source fault whereas the nearby, shallow-dipping normal, oblique, and reverse faults are subsidiary.”

Paleoseismic data further suggest a termination zone near the San Joaquin Hills and “that the San Joaquin uplift is structurally tied to the coastal system of strike-slip faults.”

**GEOMORPHOLOGY**

“The level of activity is indicated by both the relatively large lateral deflections of stream channels that are incised into low marine terraces (Figure A-4-4), and by the results of the three-dimensional trenching. These observations suggest a lateral slip rate of about 2 mm/yr during the late Quaternary (Rockwell, 2010a).”

“For the southern termination, the right-step between the Rose Canyon and Descanso faults forms the depression occupied by San Diego Bay (Figure A-4-1, and is likely large enough (>5 km) to arrest dynamic slip.”

**OTHER**

“… I suggest using the maximum slip rate range of 1.1 to 2.5 mm/yr, with the best estimate of 1.5-2.5 mm/yr, with the following weights: 0.5 (0% weight), 1.0 (10% weight), 1.5 (30% weight), 2.0 (40% weight), 2.5 (20% weight), and 3.0 (0% weight).” In order to accommodate the possibility of clustering “I would suggest using the long-term rate (the above) with an 80% weight, and consider using an alternate weighting scheme for slip rate (in mm/yr) with a 20% overall weight as follows: 0.5 (0% weight), 1.0 (10% weight), 1.5 (30% weight), 2.0 (30% weight), 2.5 (20% weight), and 3.0 (10% weight).”


**STRUCTURAL**

Does not see OBT as single large structure, but rather small segments reactivated, possibly by block rotation and localized transpression in the San Diego Trough/Gulf of Santa Catalina region.


At the behest of the California Geological Survey, the extent of the OBT was mapped using industry MCS data available at the USGS NAMSS web site. The main OBT reflector is quite strong and well imaged off of San Mateo point (e.g., Crouch and Suppe, 1993). Following this prominent reflector on strike lines that extend along most of the Gulf of Catalina, it was not possible to tie the reflector to the OBT mapped south of the area around San Mateo Point. Hence, it is difficult to justify a pervasive areal extent of the OBT.

High-resolution reflection profiles imaging folds within the hanging wall of the OBT show reflectors with increasing tilt with depth behind one of the prominent folds. Although this may indicate active folding/uplift, it is not possible to preclude the possibility that the progressively tilted beds are from sediment waves, which are pervasive in the area owing to the close proximity of the San Mateo channel and fan system.

Notes no evidence for Holocene connection between Coronado Banks Fault and Palos Verdes Fault, contrary to what is depicted in UCERF 2 and the CFM.
New USGS surveys planned for spring and summer of 2010.

SEISMOLOGY

- Comparison of the newly acquired map trace of the San Diego Trough Fault (as was currently being refined by Conrad, J.E.) with the Astiz and Shearer (2000) relocated epicenters of the 1986 Oceanside events indicates the earthquakes very clearly match a right step in the San Diego Trough Fault, which clearly explains the oblique thrust focal mechanisms in this earthquake sequence rather than the model presented in Rivero et al. (2000) and Rivero (2004).


STRUCTURAL

- 1986 Oceanside thrust earthquake and “extensive research of hundreds of proprietary oil industry marine geophysical seismic reflection survey lines, lead us to infer the presence of two distinct, active thrust fault systems located offshore of southern Orange County and San Diego County.”
- The “OBT extends at least from Laguna Beach to the Mexican border and may dip under the shoreline.”
- “The slip rate was estimated for the OBT based on measures of fault offsets and uplift using the marine geophysical seismic reflection survey data and estimates of the ages of the deformed geologic formations.”
- “We recognize that others believe that right-lateral strike slip faults (model 1) dominate the tectonics off-shore of Orange and San Diego Counties. However, based on the currently available data, we would assign a weight of ‘0’ to rupture model 1 [as it] is not kinematically compatible with the large amount of displacement we document on the OBT.”
- “[I]t is unclear whether the shallow dipping thrust faults (such as the OBT) are primary seismic source faults, with the steeply dipping, right-lateral, strike-slip faults, such as the Ni or RC faults, being subsidiary, or whether the steep, strike-slip faults are the primary seismic sources, and the thrust faults are subsidiary.”
- “Association of the OBT and the San Joaquin Hills thrust, combined with the patterns of uplifted coastal marine terraces, further support fault activity.”
- “At the depths and locations where data is necessary to resolve the uncertainty...regarding the intersection between the NI/RC and the OBT, the faults are within the basement rocks and the velocity contrast/acoustic impedance of the basement rocks either side of where these faults are inferred to be interacting is not likely to be significant enough to produce adequate reflectors in the marine geophysical seismic reflection surveys.”
- “[I]t is doubted whether high energy, deep penetrating 2-D or 3-D seismic surveys can retrieve the necessary data to be able to unequivocally resolve this particularly important uncertainty.”

SEISMOLOGY
“[R]everse/thrust focal mechanism solution tied to the offshore 1986 Oceanside (M_L 5.3) Earthquake demonstrated that active blind thrust faults also exist in Southern California’s inner Continental Borderland.”

GEODETIC

Research and analysis considered “GPS data from the SCEC Crustal motion Map that Kier and Mueller (1999) used...our sense is that these geodetic data are poorly constrained....Thus, there is a large uncertainty with this rate deformation, but at present we simply lack another means to estimate this rate.”


STRUCTURAL

“Given its structural context the ABF should be characterized by a significant component of contractional dip-slip motion. However, the ABF is uniquely characterized by nearly pure strike-slip displacements along the east-west trending eastern portion and an increasing normal component of dip-slip motion along western segments where its trend becomes more northwesterly.”

“The net effect is to connect regions of high extension in the Gulf of California with those in the northern Continental Borderlands.”

“However, the kinematics and distribution of faults that accommodate the plate motion exhibit profound along-strike variations and the margin can be separated into three distinct tectonic domains.”

“The Gulf of California forms the southern segment of the plate margin where a system of en echelon transform and spreading centers accommodate integrated transtensional shearing across a relatively narrow deformation belt along the axis of the gulf.”

“In the northern plate-boundary segment, most of the shearing is accommodated by the San Andreas Fault system. Dextral strike-slip faults in this domain are kinematically coordinated with folds and thrust faults to produce strongly transpressional shearing.”

“In the central domain of the plate margin, shearing is marked by the “Big Bend” of the San Andreas Fault, which “[l]inks plate-margin shearing along coastal California with that in the Gulf of California. In many ways the central domain is a transitional region between the two radically different domains to the north and south. However it also has unique pattern of faulting that is distinct from the other two domains. Although thrust faults and folds are present throughout the northern half of the central domain (Zoback and Zoback, 1980; Bartley et al., 1993) horizontal contraction is largely accommodated by conjugate strike-slip faults.”

Major late Miocene normal faults form an important kinematic component of deformation in the southern half of the central domain, but extreme crustal thinning is partially compensated by north-south shortening associated with detachment folds and conjugate strike-slip faults.