Develop Geological Model of Offshore Southern California (Borderland) for the Community Rheology Model

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INTRODUCTION

The California Continental Borderland offshore southern California (Borderland) is a complex part of the broad Pacific-North America transform plate boundary. Major active faults in the Borderland are capable of producing strong earthquakes which may be destructive to coastal and offshore facilities. Although most of the major active faults and the regional geology of the Borderland have been mapped to some extent (Moore, 1969; Vedder, 1987), much of this data is lacking in the SCEC Community Models. The Community Rheology Model (CRM) being developed requires a more comprehensive geology model (GF) for use in developing more accurate models of regional deformation and earthquake potential. Here we present an initial GF model for the offshore southern California (Borderland).

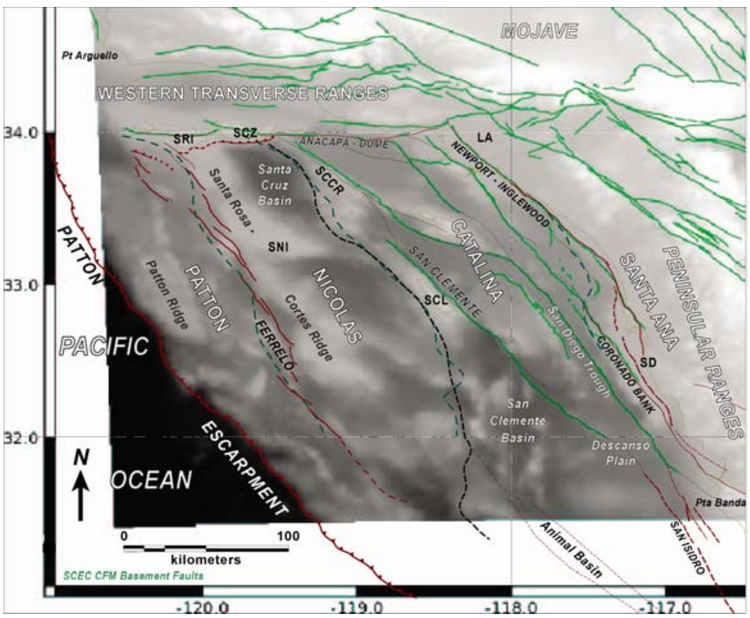

Figure 1. Map showing major tectono-stratigraphic terranes of the northern California Continental Borderland [modified from Vedder, 1987; Crouch and Suppe, 1993]. Red faults and green and black dashed lines show approximate terrane boundaries.

The initial model will be simple, consisting of the major crustal blocks previously defined as the distinctive tectonostratigraphic terranes (Fig. 1; Howell et al. 1981; Vedder, 1987). The block boundaries have been inferred as major fault zones active during the tectonic evolution of the southern California region during periods of subduction, oblique-rifting, and present day transform faulting along the Pacific-North America plate boundary (Vedder, 1987; Bohannon and Geist, 1998). However, as noted by Crouch and Suppe (1993), “The boundaries between the LAB-IB rift and its three surrounding lithotectonic belts lie deeply buried both onshore and offshore, so none is well-defined, and their precise locations remain controversial.” The first objective of this project is to define these boundaries more accurately based on recently published data. For the initial Borderland model, these complex boundaries will be simply defined, but the various structural configurations that may represent the tectonic character of these boundaries will be discussed. The simple model will be further defined by a set of crustal and upper mantle geology columns that describe the material properties of each block including density, seismic velocity, layer thickness, geometry, and lithology (simplified). The latter may also include items important for determination of rheological properties of the block, e.g. anisotropy, fluid content, mineralogy, temperature, but these details will be refined in future updates of the model.

CRUSTAL BLOCK BOUNDARIES

Inner Borderland Rift (Catalina Terrane) – Western Batholith (Santa Ana Terrane) Boundary

The tectonic boundaries of the Inner Borderland Rift are complex. The boundary between the Catalina and Santa Ana terranes juxtaposes contrasting basement lithology – exhumed subduction complex of underplated high pressure metamorphic rocks known as Catalina Schist (Platt, 1976) against the felsic plutonic rock basement of the Peninsular Ranges batholith (Howell et al. 1987). The boundary is represented by the breakaway where the Western Transverse Ranges crustal block was rifted from the continental margin. Subsequent vertical-axis clockwise rotation and oblique extension (transtension) removed the former forearc terrane to its present location and transverse orientation to the transform plate boundary. Initially, Vedder (1987) modeled this boundary as the vertical Newport-Inglewood-Coronado Bank fault system.

Inner Borderland – Outer Borderland: Catalina Terrane – Nicolas Forearc Boundary

The boundary between the Outer Borderland and the Inner Borderland juxtaposes the forearc basement terrane against the exhumed subduction complex (high pressure metamorphic) Catalina Schist basement terrane (Figs. 1&2; Vedder, 1987). The eastern boundary of the Nicolas terrane is a breakaway resulting from the rifting of the Outer Borderland crustal block from the northern Baja California part of the Peninsular Ranges batholith (Crouch, 1979; Legg, 1991). The Nicolas-Catalina terrane boundary has undergone major strike-slip – about of 120 km or more represented as the distance from the north end of the Nicolas terrane to an initial position near Punta Banda since the early Miocene rift initiation. The southern end of the Outer Borderland Nicolas forearc block is poorly defined by existing data, but presumably would have been adjacent to the north edge of intact subduction zone terranes north of Vizcaíno Basin). For a simple block model to investigate offshore tectonic deformation, we suggest using the San Clemente (Santa Cruz-Catalina Ridge-San Clemente-San Isidro) fault zone (Fig. 1) as a vertical boundary to accommodate the major right-slip that must have occurred along this important terrane boundary. The actual boundary is likely to be a complex transpressional fault system (Legg et al. 2015), consisting of steep strike-slip and moderate-dipping oblique-slip faults along the East Santa Cruz Basin fault zone and unmapped faults to the south.

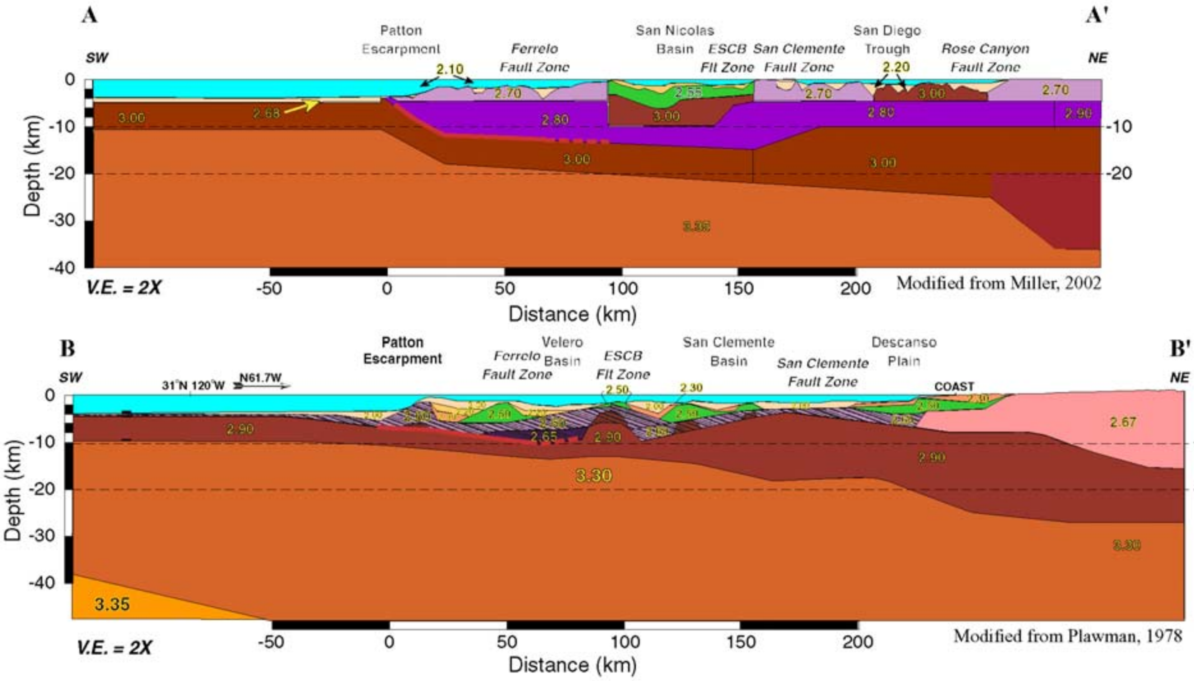

Figure 2. Cross-sections of Borderland crustal structure showing inherited subduction zone structure at depth and extended accretionary wedge and forearc upper crust. Top profile crosses the northern Borderland and coast near Oceanside. Bottom profile crosses more highly extended southern Borderland crust across San Clemente Basin west of Ensenada, Baja California

Outer Borderland: Patton Accretionary Terrane – Nicolas Forearc Boundary

The Ferrelo fault zone is a major northwest-trending strike-slip fault zone that lies near the western edge of the Nicolas forearc terrane (Fig. 1). The transpressional Ferrelo fault zone follows the western flank of the Santa Rosa-Cortes Ridge, which is recognized as a structurally-inverted basin filled with late Cenozoic (upper Cretaceous to Miocene) sedimentary rocks (Crouch, 1981; Schindler, 2010). The boundary between the Nicolas and Catalina terranes was formally defined as the western edge of the Eocene and older forearc basin rocks (Howell et al. 1987; Vedder,1987), but this boundary lies slightly farther west (up to 15 km) of the Ferrelo fault zone (Fig. 1). Like the eastern boundary of the Nicolas terrane, where the edge of forearc rocks is irregular and not clearly delimited by a major active fault zone, we recommend using the Ferrelo fault zone as the active tectonic boundary between Patton and Nicolas terranes. The Ferrelo fault zone has not been incorporated into the SCEC Community Fault Model. Schindler (2010) mapped the fault using deep penetration multichannel seismic profiles and interpreted a moderate east dip (~45º), whereas Vedder (1987) used a simple vertical fault boundary. For this preliminary model, a vertical fault will be provided based on steep (65º E dip) northwest-trending focal plane from a moderate (M4.0) earthquake recorded in the area (Legg et al. 2015).

Outer Borderland: Patton Accretionary Terrane – Pacific (Oceanic Crust) Boundary

The western boundary of the Outer Borderland and the Patton accretionary terrane is represented by the fault along the base of the Patton Escarpment (Fig. 1). The boundary is the former subduction megathrust that may remain active (potentially-active) to accommodate some relative motion between the oceanic crust of the Pacific plate to the west and the Borderland above and to the east (Legg et al. 2015). The top of subducted oceanic crust beneath the base of the Patton Escarpment was interpreted in deep penetration USGS and exploration industry seismic profiles (Miller, 2002) and modeled using gravity data (Plawman, 1978; Miller, 2002). This surface appears to have a dip of about 22º (20º-25º) on the northern profiles (Fig. 2; Miller, 2002; Shor et al. 1976), but shallows to about 6º (5º-6º) beneath the highly extended Southern Borderland (Plawman, 1978).

CRUSTAL BLOCK GEOLOGIC COLUMNS

The preliminary version of the Borderland Geologic Framework consists of simple 1-D crustal and upper mantle geologic columns (Fig. 3). Because of the complex geometry and subseafloor geology, the tectonostratigraphic columns shown include a simple 1-D version plus additional columns with dipping layer interfaces that represent the transition between terranes along the edges of the Inner and Outer Borderland. The columns show the compressional seismic wave velocity based on seismic refraction measurements (Shor et al. 1976; Ten Brink et al. 2000; Hauksson, 2000) within each layer and a simplified lithology or geologic description from published geophysical and geological models (Shor et al. 1976; Vedder, 1987; ten Brink et al. 2000; Miller, 2002; Plawman, 1978; Bowden et al. 2016). The table provides the layer thickness, P-wave and S-wave velocities, and densities for the model. For simplicity in this initial model, simple broad lithologic character is provided based on the density and seismic velocity structure derived from the geophysical cross-sections (Fig. 2). Vedder (1987) divided the basement rocks of the four terranes as Coastal Belt Franciscan for the Patton Accretionary Wedge, Coast Range Ophiolite for the Nicolas Forearc, and Catalina Schist for the Catalina Inner Borderland Rift.

Inner Borderland Rift (Catalina Terrane)

The Inner Borderland Rift is represented by two columns in the simple model (Fig. 3): Catalina Basin and Catalina Ridge. The basin column represents the deep water areas including Santa Monica, San Pedro, San Diego Trough, and Catalina basins, whereas the ridge column includes Santa Catalina Island and the Santa Cruz-Catalina Ridge area where basement rocks are exposed at the seafloor. Although the island rises above ocean, the simple model is truncated at sea level. Middle Miocene igneous rocks intruded during oblique rifting and Mesozoic metamorphic rocks associated with exhumed Catalina Schist (underplated subduction complex - melange) comprise the major shallow crustal basement rocks. A deep crustal layer of meta-basalt and gabbro, representing underplated oceanic crust and sediments (meta-graywacke) represents the higher velocity layer which overlies upper mantle rocks including serpentinite. Corbett (1984) derived a three-layer model with an intermediate crustal layer about 17 km thick and P-wave velocity of 6.2-6.3 km/sec above Moho at 22 km depth. Ten Brink et al (2000) interpret a homogeneous lower crust of Catalina Schist with a P-wave velocity of 5.3-5.6 km/sec, Moho at 19-24 km depth and no high velocity layer in the lower crust (except possibly below 15 km where magmatic underplating or pre-existing oceanic crust may exist. Miller (2002) modeled gravity data to infer deep crustal magmatic layers with higher density (3.0 gm/cm^3) that would be consistent with the deep high velocity layer. The deep crustal layer may also include igneous intrusions related to plutonic rocks exposed at Santa Catalina (Smith, 1897) and other Inner Borderland volcanic centers. Clearly, a single geologic column for the Catalina terrane (or any other) will be oversimplified. The two columns presented are a compromise that may be refined in future versions of the Geologic Framework.

Outer Borderland Forearc (Nicolas Terrane)

The Outer Borderland Forearc (Nicolas terrane) is represented by three simple columns: one column for the Santa Rosa Ridge (1-D model) and two basin columns including the larger Santa Cruz Basin at the north and San Nicolas Basin in the central area. The Santa Cruz Basin column shows a transition from ridge to basin, whereas the San Nicolas Basin is another simple 1-D column. The basement beneath the forearc basin and younger sediments is interpreted as oceanic crust similar to the Coast Range Ophiolite north of the Western Transverse Ranges (Vedder, 1987). This interpretation is based on the higher seismic velocities compared to the Catalina Schist of the Inner Borderland (Shor et al. 1976), and to a large magnetic anomaly along the eastern side of the terrane (Miller, 2002). Outcrops including the Willows Diorite at Santa Cruz Island and scattered occurrences of saussurite gabbro around the edges of the Nicolas forearc terrane support this interpretation (Vedder, 1987). Beneath the ophiolite is a layer of Catalina Schist, based on the density model and gravity data (Miller, 2002). The seismic refraction data were unable to identify this low velocity zone (Shor et al. 1976). Deep crustal (20 km) shear wave velocities derived from ambient-noise cross-correlation functions (Bowden et al. 2016) are relatively low in the areas of transpression including the Santa Rosa-Cortes Ridge and along the Western Transverse Ranges boundary, which may be related to crustal thickening and possibly deep fluids.

Outer Borderland Accretionary Wedge (Patton Terrane)

The Outer Borderland Accretionary Wedge columns include three variations from the Patton terrane and a Pacific Ocean (oceanic crust) terrane for comparison (Fig. 3). The Patton Ridge terrane represents the simple 1-D column for the accretionary wedge. The Tanner Basin column includes dipping layer boundaries into the adjacent basins to the east, whereas the Patton Escarpment column includes the southwest slope of the seafloor at the escarpment and northeast dip of the deeper layers of subduction complex and Moho. A relatively thin layer of Neogene sediments covers thicker layers of Franciscan subduction complex, deeper Catalina Schist (high-P, low-T metamorphic melange), and remnant Farallon oceanic crustal slab with progressively greater metamorphism to the east, deeper in the former subduction zone. Thickening of the lower oceanic crustal gabbroic rock layer beneath the Outer Borderland is may result from imbrication or underplating during prior subduction (Couch & Riddihough, 1989) or from continued magmatic underplating and volcanic activity along the Patton Escarpment (Bowden et al. 2016).

SUMMARY

The basement geology of the California Continental Borderland is a modified subduction zone accretionary wedge and forearc that has been stretched during Miocene oblique rifting and squeezed to the north by increasing transpression related to collision with the Western Transverse Ranges. Extreme extension within the Inner Borderland Rift (and Southern Borderland) produced widespread volcanism and intrusion of calc-alkaline magmas associated with decompression melting of subducted and underplated material and above local slab windows and gaps to the upper mantle of the former Farallon plate. Extension within the forearc due to wedge collapse uplifted underplated high pressure, low temperature, metamorphic rocks (blueschists) which eventually were exhumed and eroded into adjacent sedimentary basins during the Miocene plate boundary reorganization. Along with rift associated magmatism, a core complex formed within the highly extended terranes – Catalina and Southern Borderland – which represent the rifts left behind by the northwest translation of the Outer Borderland forearc and accretionary terranes including the vertical-axis rotation of the Western Transverse Ranges. Extension persists in some area, particularly in the Southern Borderland and locally in the Outer Borderland (Patton terrane) and Pacific lithosphere to the west where seamount volcanoes show activity from middle Miocene to Holocene epochs. Quaternary volcanism is present along the northwestern Baja California coast including Punta Collnett and San Quintín. The complex tectonic evolution has produced widely varying lithologic character that continues to control the regional deformation along complex fault systems that include high-angle strike-slip and moderate to low-angle oblique-slip and thrust faulting. Large earthquakes produced in this complex system are likely to be equally complex and involve multiple faults and fault segments in unexpected combinations. The challenge to develop simple and realistic earth models of this active deformation cannot be understated, and will require innovative depiction of the complex structure within the Geologic Framework in order to evaluate earthquake potential accurately.

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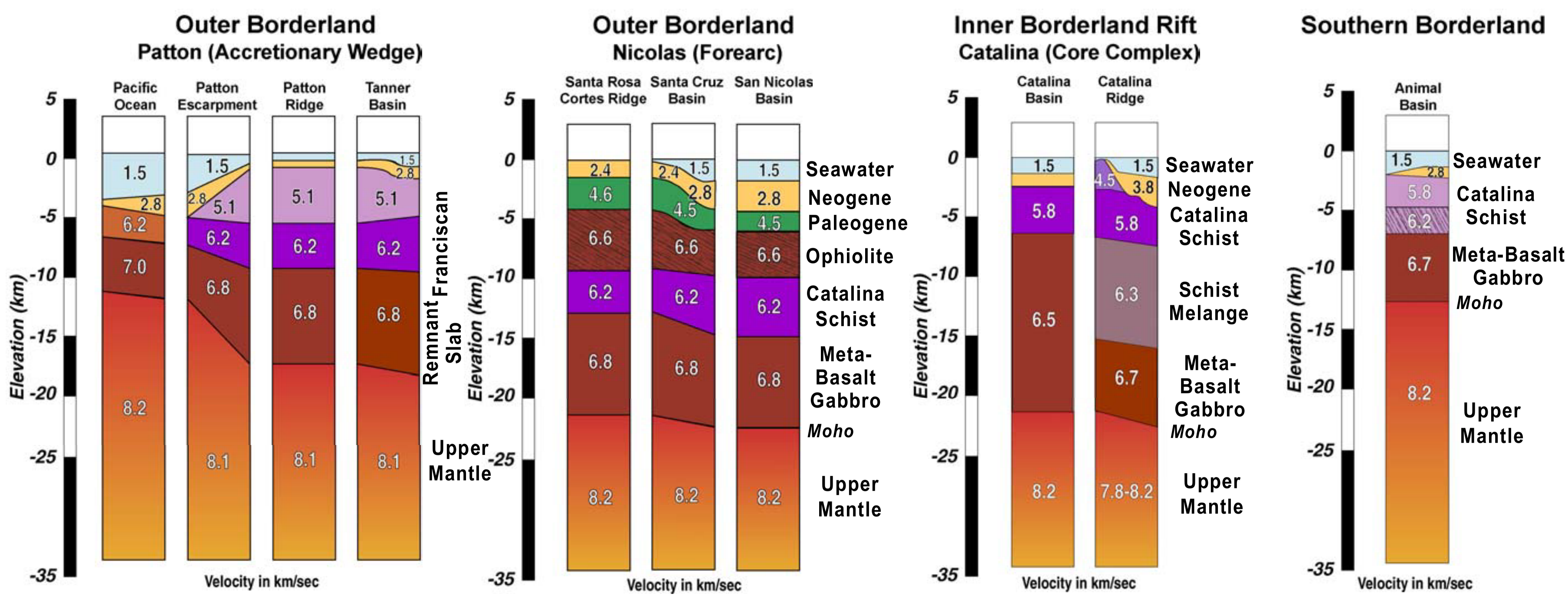
Borderland Geologic Framework for the SCEC Community Rheology Model



Borderland Tectono-Stratigraphic Columns (1-D)

Pacific				Patton				Nicolas				Catalina				Southern Borderland			
D	Vp	Vs		D	Vp	Vs		D	Vp	Vs		D	Vp	Vs		D	Vp	Vs	
0	1.50	0.0	1.03	0	1.50	0.0	1.03	0	1.50	0.0	1.03	0	1.5	0.0	1.03	0	1.5	0.0	1.03
4.0	2.8	1.6	2.68	1.00	2.80	1.6	2.72	1.0	2.8	1.6	2.55	0.75	3.8	2.1	2.6	2.0	2.8	1.6	2.55
6.0	6.7	3.8	3.00	2.0	5.1	2.9	2.81	3.0	4.5	2.5	3.05	2	4.5	2.5	2.72	2.3	5.8	3.3	2.85
7.0	7.0	3.9	3.36	6.0	6.2	3.6	2.9	5.0	6.6	3.8	2.85	4	5.8	3.3	2.85	5	6.2	3.6	2.9
12.0	8.2	4.0	3.36	12	6.8	3.9	3.0	8.0	6.2	3.6?	3.0	7	6.5	3.7	2.9	7	6.7	3.8	3.0
20		4.2		18	8.1	4.2	3.36	13	6.8	3.9	3.0	22	8.2	4.0	3.36	12.5	8.2	4.0	3.36
30		4.4		30		4.4		20	8.2	4.0	3.36	30		4.3		30			4.3
50		4.3		50		4.5		30		4.3		50		4.6		50			4.6
								50		4.5									
km	km/s	km/s	g/cm³	km	km/s	km/s	g/cm³	km	km/s	km/s	g/cm³	km	km/s	km/s	g/cm³	km	km/s	km/s	g/cm³

Figure 3 – Borderland Geologic Columns (version 1)

REFERENCES

Bohannon, R. G., and Geist, E. (1998). Upper crustal structure and Neogene tectonic development of the California Continental Borderland. *Geological Society of America Bulletin*, **110**, 779-800.

Bowden, D. C., M. D. Kohler, V. C. Tsai, and D. S. Weeraratne (2016), Offshore Southern California lithospheric velocity structure from noise cross-correlation functions: *J. Geophys. Research: Solid Earth*, *121*, 3415-3427.

Corbett, E. J. (1984), Seismicity and crustal structure studies of southern California: Tectonic implications from improved earthquake locations [PhD Thesis], Pasadena, California Institute of Technology, 231 pp.

Couch, R.W., and R. P. Riddihough (1989), The crustal structure of the western continental margin of North America, Ch. 8 *in* Pakiser, L. S., and W. D. Mooney, eds., *Geophysical Framework of the Continental United States*, Boulder, Colorado, Geological Society of America Memoir **172**, 103-128.

Crouch, J. K. (1979), Neogene tectonic evolution of the western Transverse Ranges and California Continental Borderland: *Geological Society of America*, v. 9-, p. 338-345.

Crouch, J. K. (1981), Northwest margin of California Continental Borderland: Marine geology and tectonic evolution, *American Assoc. Petroleum Geologists*, *65*, 191-218.

Crouch, J. K., & Suppe, J. (1993). Late Cenozoic tectonic evolution of the Los Angeles basin and inner California borderland: A model for core complex-like crustal extension. *Geol. Soc. America Bulletin*, **105**, 1415-1434.

De Hoogh, G. L. (2012), Structural and stratigraphic evolution of the central and southern Outer California Continental Borderland, unpublished M.S. Thesis, California State University, Long Beach, 66 pp.

Hauksson, E. (2000), Crustal structure and seismic distribution adjacent to the Pacific and North America plate boundary in southern California: *Journal of Geophysical Research*, v. 105, B6, p. 13875-13903.

Howell, D. G., and J. G. Vedder (1981), Structural implications of stratigraphic discontinuities across the southern California borderland; *in* Ernst, W.G., ed., *The Geotectonic Development of California, Rubey Volume 1*: Prentice-Hall, Inc. Englewood Cliffs, New Jersey, 535-558.

Howell, D. G., D. E. Champion, and J. G. Vedder, (1987), Terrane accretion, crustal kinematics, and basin evolution, southern California; *in* Ingersoll, R.V., and Ernst, W.G., ed., *Cenozoic Basin Development of Coastal California, Rubey Volume V1*: Prentice-Hall, Inc. Englewood Cliffs, New Jersey, 242-258

Legg, M.R. (1991), Developments in understanding the tectonic evolution of the California Continental Borderland: *in* Osborne, R.H., ed., *From Shoreline to Abyss: Shepard Commemorative Volume*, SEPM SP 46: 291-312.

Legg, M. R., M. D. Kohler, N. Shintaku, and D. S. Weeraratne (2015), High-resolution mapping of two large-scale transpressional fault zones in the California Continental Borderland: Santa Cruz-Catalina Ridge and Ferrelo, Journal of Geophysical Research: Earth Surface, **120**, doi:10.1002/2014JF003322.

Miller, K. C. (2002), Geophysical evidence for Miocene extension and mafic magmatic addition in the California Continental Borderland. *Geological Society of America Bulletin*, v. 114, p. 497-512.

Moore, D. G. (1969). *Reflection profiling studies of the California Continental Borderland--Structure and Quaternary turbidite basins*. Geological Society of America Special Paper **107**, 142 p.

Plawman, T. L. (1978), Crustal structure of the Continental Borderland and the adjacent portion of Baja California between latitudes 30°N and 33°N, Unpublished M.S. Thesis, Oregon State University, Corvallis, Oregon, 72 pp.

Platt, J. P. (1976), The significance of the Catalina Schist in the history of the southern California Borderland, *in*, Howell, D. G., editor, Aspects of the Geological History of the California Continental Borderland: Pacific Section, American Association of Petroleum Geologsts, Miscellaneous Publication 24, p. 47-52.

Schindler, C. S. (2010), 3D fault geometry and basin evolution in the northern Continental Borderland offshore southern California, unpublished M.S. thesis, California State University, Bakersfield, 42 pp,

Shor, G. G., Jr., R. W. Raitt, and D. D. McGowan (1976), Seismic refraction studies in the southern California borderland, 1949-1974: Scripps Institute of Oceanography *Reference 76-13*, 70 p.

Ten Brink, U. S., J. Zhang, T.M., Brocher, et al. (2000), Geophysical evidence for the evolution of the California Inner Continental Borderland as a metamorphic core complex. *J. Geophys. Research*, **105**, 5835-5857.

Vedder, J. G., (1987), Regional geology and petroleum potential of the southern California borderland: *in* Scholl, D. W., Grantz, A., and Vedder, J. G., eds., Geology and resource potential of the continental margin of western North America and adjacent ocean basins, Beaufort Sea to Baja California: Circum-Pacific Council for Energy and Mineral Resources, Houston, Texas, Earth Science Series, **6,** 403-447.