The California Continental Borderland

SCEC White Paper 2019

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The California Continental Borderland (CCB) offshore southern California accommodates an estimated 20% of the Pacific-North American (P-NA) plate motion (Fig. 1) (Bennett et al., 1996; Platt and Becker, 2010), has experienced historic seismicity including several M5+ events (Fig. 2) (Astiz and Shearer, 2000; Hauksson et al., 2012), and hosts long and continuous fault zones capable of generating large (M7+) earthquakes (Legg et al., 2015; Sahakian et al., 2017), and potentially tsunamis (McCulloch, 1985; Borrero et al., 2004; Lee et al., 2009). Despite the potential hazard they pose to the densely populated coastal regions of southern California, faults in the CCB are less well understood than their onshore counterparts. For example, slip rates and recurrence intervals are poorly determined for the major CCB fault systems and very little is known about interactions among fault systems within the CCB.

Multidisciplinary, multi-institutional efforts are needed to address the complexities of tectonic deformation and earthquake processes. Other NSF initiatives have focused on rift and subduction margins (e.g., NSF Margins, GeoPRISMS), but SCEC is uniquely positioned for multidisciplinary research to assess plate-boundary scale tectonics across a strike-slip margin. With as much as 20% of P-NA plate motion occurring in the CCB, an expansion of SCEC's natural laboratory to include this region would strengthen SCEC's ability to address questions about long term and recent plate boundary evolution and how current plate motion is distributed across the broad zone of faulting that currently characterizes the plate boundary in southern California (~400 km from the San Andreas fault to Patton Escarpment) (Fig. 1). Given the differences between the onshore and offshore portions of the P-NA plate boundary (e.g., geology, slip rates, fault complexity, rheology, fluids), it is reasonable to hypothesize that earthquake processes may also differ. Thus, to achieve SCEC's long-term goal of improving the predictability of earthquake system models, it is vital to include data

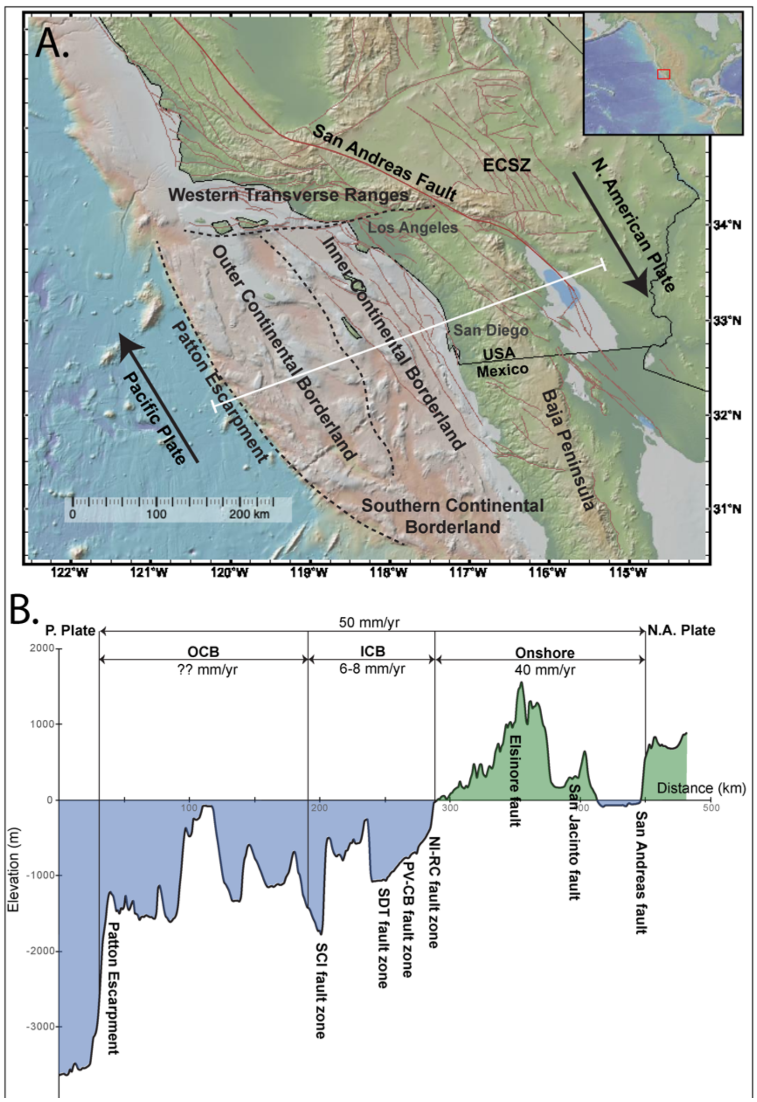

Fig. 1: Map of the CCB and major strike-slip fault systems within the P-NA plate boundary. The ICB accommodates 6-8 mm/yr of P-NA plate motion, with an unknown amount, up to an additional 5 mm/yr, accommodated in the OCB (Bennett et al., 1996; Platt and Becker, 2010). Figure made with GeoMapApp (www.geomapapp.org) / CC BY (Ryan et al., 2009).

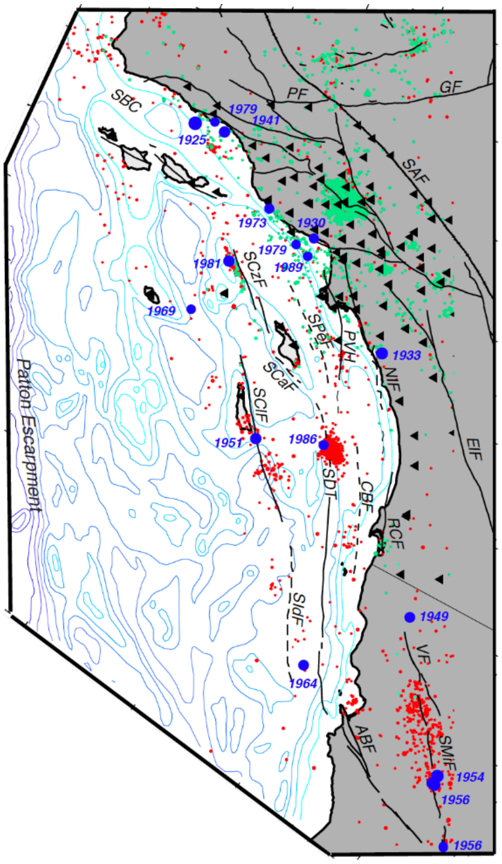

Fig. 2 (above): Map of CCB seismicity from Astiz and Shearer (2000). Blue circles = epicenters ML >5.0 events from 1920 to 1997. Seismicity from the SCSN catalog since 1981 (Red = low quality; Green = high quality). Black triangles are station locations used in locations. ABF, Agua Blanca Fault; CBF, Coronado Bank Fault Zone; ElF, Elsinore Fault; GF, Garlock Fault; NIF, Newport-Inglewood Fault; PF, Big Pine Fault; PVH, Palos Verdes Hills Fault; RCF, Rose Canyon Fault; SAF, San Andreas Fault; SBC, Santa Barbara Channel; SCaF, Santa Catalina Fault; SClF, San Clemente Fault; SCzF, Santa Cruz Fault; SDT, San Diego Trough Fault; SIdF, San Isidro Fault; SMiF, San Miguel Fault; SPeF, San Pedro Basin Fault Zone; VF, Vallecitos Fault.

from fault systems with variable properties. From the CCB, which is a major component of the plate boundary, data to support these models are severely lacking.

This white paper builds off work conducted by the SCEC Borderland Working Group, which was formed in 2002 as part of the official organizational structure of SCEC in an attempt to focus and integrate CCB research activities within the scientific mission of SCEC (Appendix A - Kohler, 2002; Appendix B - Nicholson, 2005). Here, we highlight recent advances in CCB research, identify remaining questions for the region, address ways the CCB can uniquely contribute to the SCEC natural laboratory, and propose a path forward for future research in the CCB.

Recent advances

The CCB has been an active area of research on faulting and deformation for decades (e.g., Bohannon and Geist, 1998; Crouch and Suppe, 1993; Legg, 1985; Legg et al., 2004; Lonsdale, 1991; Nicholson et al., 1994; ten Brink et al., 2000; Teng and Gorsline, 1989; Vedder, 1987), but several recent advances offer a launching point for future work. Much of the recent work was made possible through newly available, high-quality, industry seismic reflection data (e.g., Childs and Hart, 2004, DeHoogh et al., 2017; Fisher et al., 2009; Legg et al.,

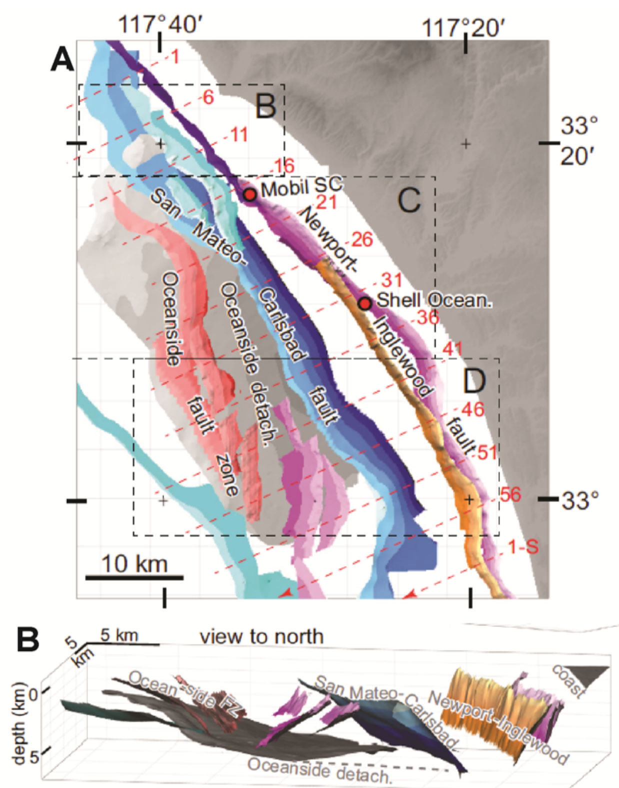

Fig. 3 (right): Low- and high-angle fault systems offshore from northern San Diego County as mapped by Sorlien et al., (2015). A) Map view of faults, including those with little evidence of Quaternary activity. Color shading changes every 1 km of depth. B) Oblique view to the north from dashed box D in Fig. 3A.

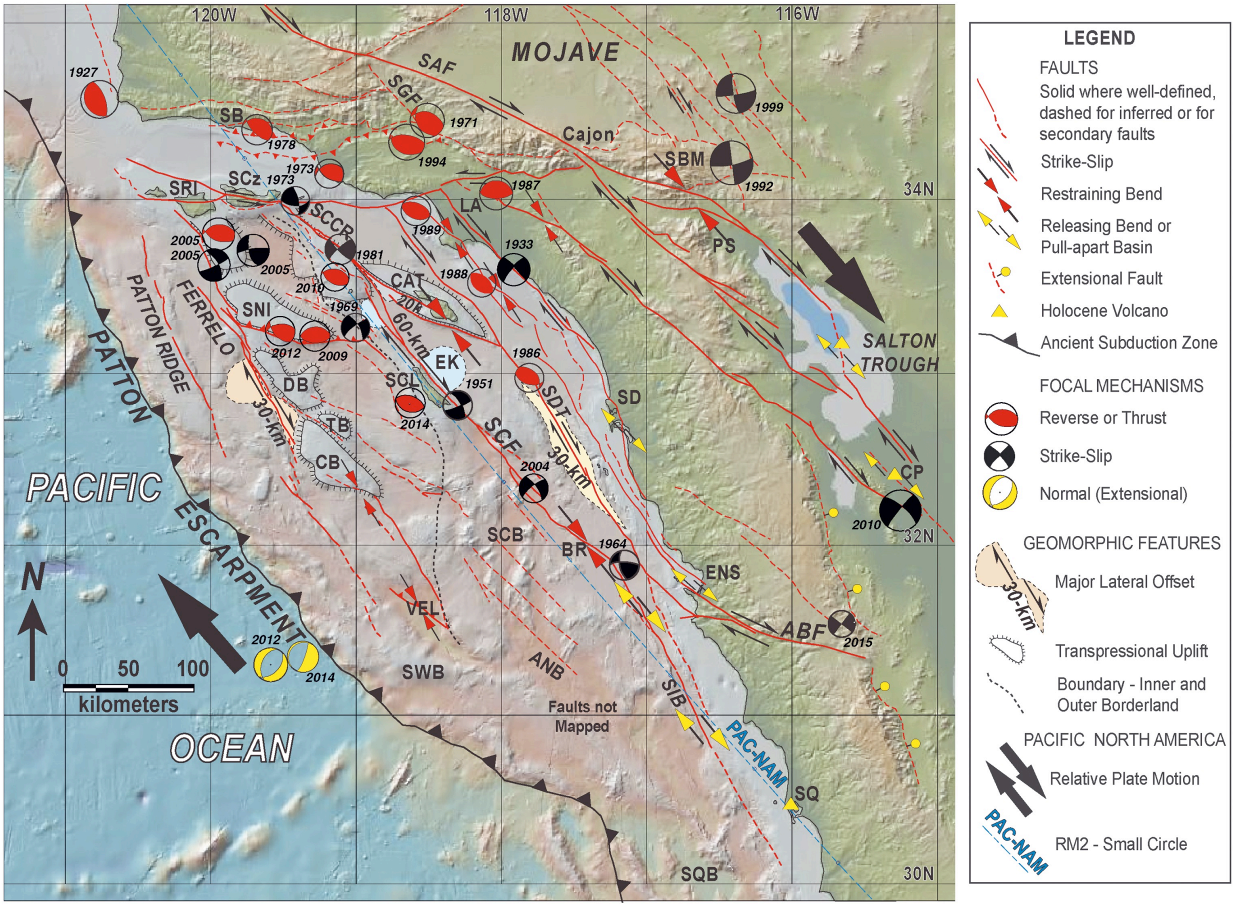

Fig. 4. Map of offshore structures and focal mechanisms from Legg et al. (2105) showing transtentional deformation in the southern Borderland and transpressional deformation in the northern Borderland, illustrating a possible "logjam" model with the Western Transverse Ranges to the north. SAF = San Andreas fault, ABF = Agua Blanca fault, SCF = San Clemente fault, SCCR = Santa Cruz-Catalina Ridge, Ferrelo, EK = Emery Knoll crater; DB = Dall Bank; SDT = San Diego Trough, CAT = Santa Catalina Island, CB = Cortes Bank, TB = Tanner Bank, SRI = Santa Rosa Island, SCz = Santa Cruz Island, SNI = San Nicolas Island, SBM = San Bernardino Mountains, SD = San Diego, ENS = Ensenada, SCB = San Clemente Basin, SIB = San Isidro Basin, SCI = San Clemente Island, SQ = San Quintin, LA = Los Angeles, PS = Palm Springs, CP = Cerro Prieto. Figure made with GeoMapApp (www.geomapapp.org) / CC BY (Ryan et al., 2009).

2015; Legg et al., 2018; Maloney et al., 2016; Rivero and Shaw, 2011; Sahakian et al., 2017; Sorlien et al., 2006, 2013; Sorlien et al., 2015), and collections of new, high-resolution seismic reflection and bathymetric data (e.g., Brothers et al., 2015; Conrad et al., 2018; Ryan et al., 2012). Many of these collaborative projects were spurred by the original SCEC Borderland working group, which reinvigorated exciting research opportunities in the CCB and resulted in major contributions to various Borderland Special Publication Volumes, including GSA Special Paper 454, "Earth Science in the Urban Ocean: The Southern California Continental Borderland" and SEPM Special Publication Number 110, "From the Mountains to the Abyss: The California Borderland as an Archive of Southern California Geologic Evolution."

Several of these recent investigations were focused on fault reactivation and the interaction between low- and high-angle faults within the CCB. The low-angle structures include a series of low-angle, E-dipping detachment faults (e.g., Thirtymile Bank and Oceanside detachments), that formed during a period of Miocene oblique extension (Fig. 3). Based on compressional structures observed in seismic reflection data above the detachments and relocated seismicity from the 1986 M5.8 Oceanside earthquake, it was hypothesized that these detachments were reactivated as Quaternary thrust faults (Rivero et al., 2000; Rivero and Shaw, 2011). With the release of more industry seismic data, improvement of data quality due to re-processing, and collection of new data, numerous investigations have now shown that the CCB is more likely characterized by transpression and transtension at bends or steps in the major CCB strike-slip fault systems (Legg et al., 2015; Maloney et al., 2016; Ryan et al., 2009; 2012; Sorlien et al., 2015). However, farther north within the CCB, other investigations revealed evidence for regional reactivation of detachments (Sorlien et al., 2013) and more evidence for transpression compared to the southern CCB, suggesting a possible “logjam” model where CCB strike-slip faults are restrained to the northwest by the Transverse Ranges (Fig. 4) (Legg et al., 2015).

Other recent efforts in the CCB used automated underwater vehicles (AUVs) and remotely operated vehicles (ROVs) to estimate Holocene slip rates for right-lateral offshore fault zones. On the San Diego Trough fault, along with traditional shipboard mapping and sampling, a very high-resolution seismic and bathymetric dataset was collected using an AUV, and sediment cores were collected with high precision using a ROV (Ryan et al., 2012). These data revealed an offset wall of the San Gabriel submarine channel that was used with radiocarbon dated sediment cores to estimate a lateral slip rate of 1.2-1.8 mm/yr for the fault (Ryan et al., 2012). Similar methods were employed along a segment of the Palos Verdes fault just south of the San Pedro Shelf, where an offset landslide scarp yielded a slip rate of 1.6-1.9 mm/yr (Fig. 5) (Brothers et al., 2015). These are the first geologic slip rate estimates on any deep-water faults in the CCB. These studies demonstrated the feasibility of determining slip rates using high-resolution methods, even in the deep-water environments of the CCB.

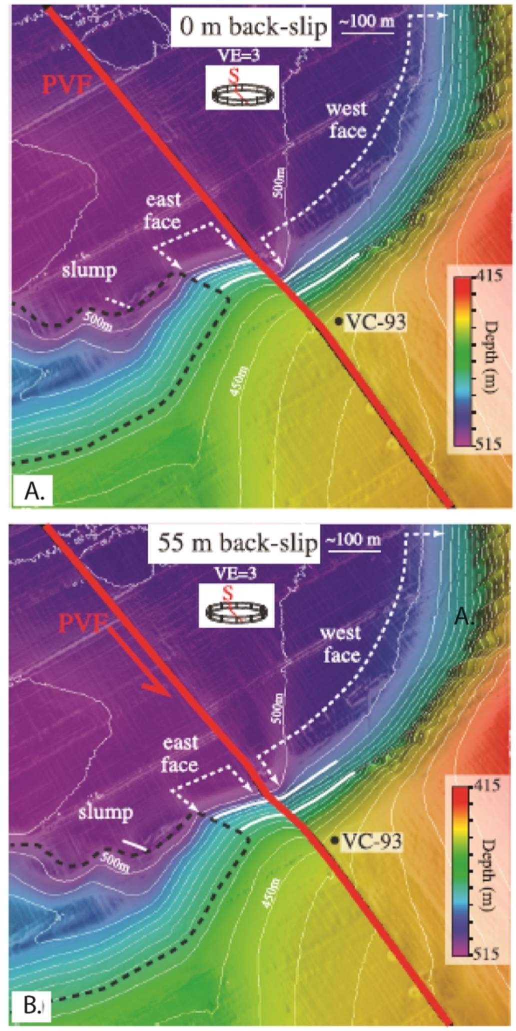

Fig. 5: Lateral offset of a headwall scarp on the Palos Verdes fault (PVF) that was used to calculate a horizontal slip rate by Brothers et al. (2015). A. Perspective view of the present-day configuration from above the upper headwall scarp looking to the southwest and oblique to the PVF. B) Perspective view following 55m of back slip applied to the eastern digital elevation model (DEM) surface.

Major Remaining Questions

How do various fault systems interact?

Despite recent advances, there is still much to learn about the active faults within the CCB. Many of the primary questions for the CCB stem from a lack of understanding of fault geometry and fault interactions. Understanding multi-segment rupture is a primary concern for seismic hazard assessment and several recent global earthquakes involved highly complex rupture patterns (e.g., 2016 Kaikoura, NZ (Hamling et al., 2017); 2010 El Mayor-Cucapah, MX (Fletcher et al., 2014); 2016 Central Italy (Scognamiglio et al., 2018). These complex ruptures have called into question previous assumptions about rupture propagation across fault steps (e.g., Wesnousky et al., 2006).

In the CCB, recent mapping of the coastal Newport Inglewood-Rose Canyon (NI-RC) fault zone indicate five offshore segments that could rupture synchronously to produce a M7.3-M7.4 earthquake (Fig. 6) (Sahakian et al., 2017). However, Coulomb stress models show that rupture propagation depends on where rupture initiates, and on details of step-over geometry. These models only included

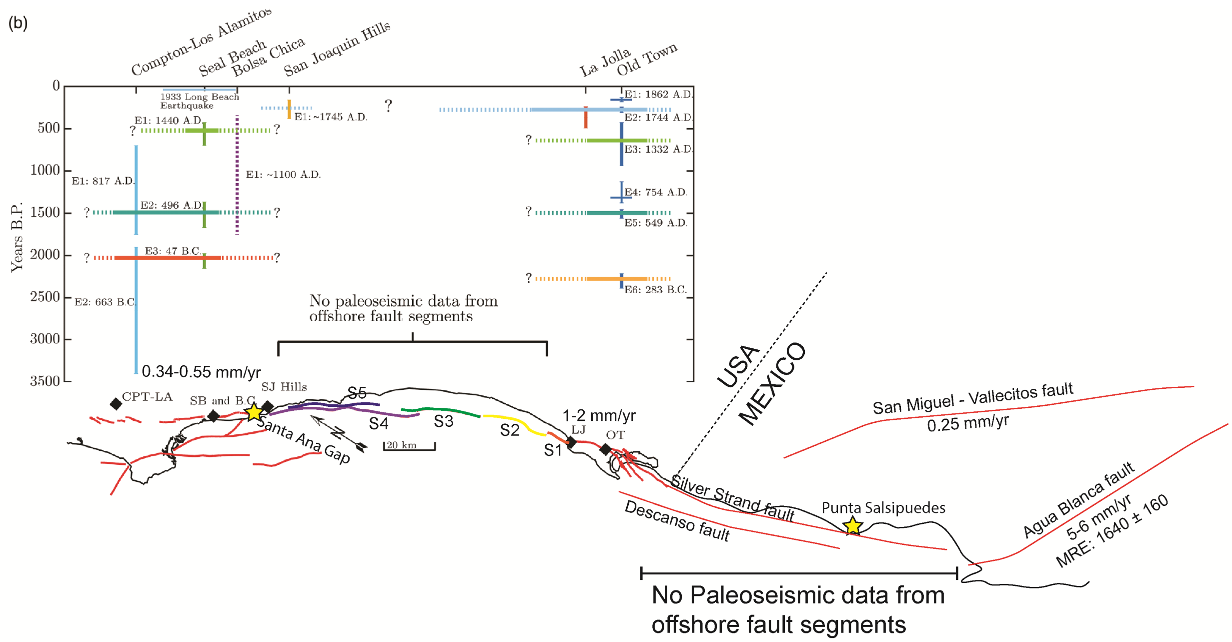

Fig. 6: Map of coastal fault zone including from north to south the Newport Inglewood fault, Rose Canyon fault, Descanso and Silver Strand faults, and Agua Blanca fault. Figure modified from Singleton et al. (2019). Offshore NI-RC fault segments S1-S5 from Sahakian et al. (2017), which have the potential to rupture synchronously to produce a M7.4 earthquake. This same section is missing paleoseismic data to compare with onshore paleoseismic records to the north and south that suggest a northward cascading series of earthquakes. Chart above fault trace map shows the reported occurrence of earthquakes at several paleoseismic sites (black squares in map) along strike of the NI-RC system. Vertical error bars are 95% confidence interval. The offshore Descanso and Silver Strand faults to the south are also missing paleoseismic records that could link the northern ruptures to ruptures on the Agua Blanca fault system in Mexico (Grant and Rockwell, 2002). Yellow stars indicate opportunities for onshore/offshore studies along this fault system that are discussed in the text. Paleoseismic data from Rockwell and Murbach (1996), Grant et al. (1997, 2002), Leon et al. (2009), and Leeper et al. (2017). CPT-LA, Compton–Los Alamitos; SB, Seal Beach; SJ, San Joaquin; LJ, La Jolla; OT, Old Town; Years B.P., years before present.

the high-angle strike slip fault segments of the NI-RC fault zone between San Diego and Los Angeles, but others have suggested the possibility for even larger, infrequent events along the NI-RC fault zone that rupture either a combination of high- and low-angle faults (Legg et al., 2018), or the entire length of the NI-RC fault system (e.g., Field et al., 2014), a distance of over 240 km. Paleoseismic records from the onshore segments of the NI-RC allow for the possibility of continuous rupture from Ensenada, Mexico to Los Angeles, but the preferred interpretation has been that of a northward cascading series of ruptures (Grant and Rockwell, 2002; Singleton et al., 2019) (Fig. 6). Resolving these various hypotheses is crucial for rupture models and hazard assessment, as this fault zone transects the densely populated coastal zone, including Los Angeles, San Diego and Tijuana, Mexico. Evaluating the timing of events on the offshore segments of the NI-RC would be particularly helpful in this regard, and would also contribute to improved understanding of earthquake cycle models and transfer of slip between fault segments with variable geometry.

Additional questions remain about fault reactivation, as some detachments within the CCB are characterized by reverse or oblique-reverse reactivation, while others are not and appear offset by high angle strike slip fault zones (e.g., Sorlien et al., 2013, 2015; Legg et al., 2015). The regional scale patterns of fault reactivation are not well known, but could contribute to a better understanding of strain partitioning and the relationships between stress fields and fault orientation (e.g., Fletcher et al., 2016). Furthermore, the northwest-trending faults of the CCB intersect the more E-W structural trend of the Transverse Range Province to the north, but little is known about the termination of the CCB fault zones and possible linkages to faults to the north. This is a critical gap because faults within the offshore portion of the Transverse Range Province are characterized by reverse slip, which has the potential to generate tsunamis.

What are the slip rates and recurrence intervals on CCB fault systems?

Most of what we know about slip rates in the CCB is derived from limited GPS measurements and geologic rates from onshore fault segments. There are no existing slip rate estimates for fault systems in the Outer Borderland. Nevertheless, two recent slip rate estimates from deep water fault segments in the Inner Borderland demonstrated the feasibility of gathering these data from faults across the CCB (Ryan et al., 2012; Brothers et al., 2015) (Figs. 5 & 7). The current sparse slip rate estimates also bring up questions about slip transfer between fault systems because there is apparent variability in observed slip rate along strike (Fig. 7). For example, the NI-RC Holocene right-lateral slip rate varies from 1-2 mm/yr onshore in San Diego (Lindvall and Rockwell, 1992) to 0.34-0.55 mm/yr (minimum rate; Grant et al., 1997) onshore in northern Orange County (Fig. 7).

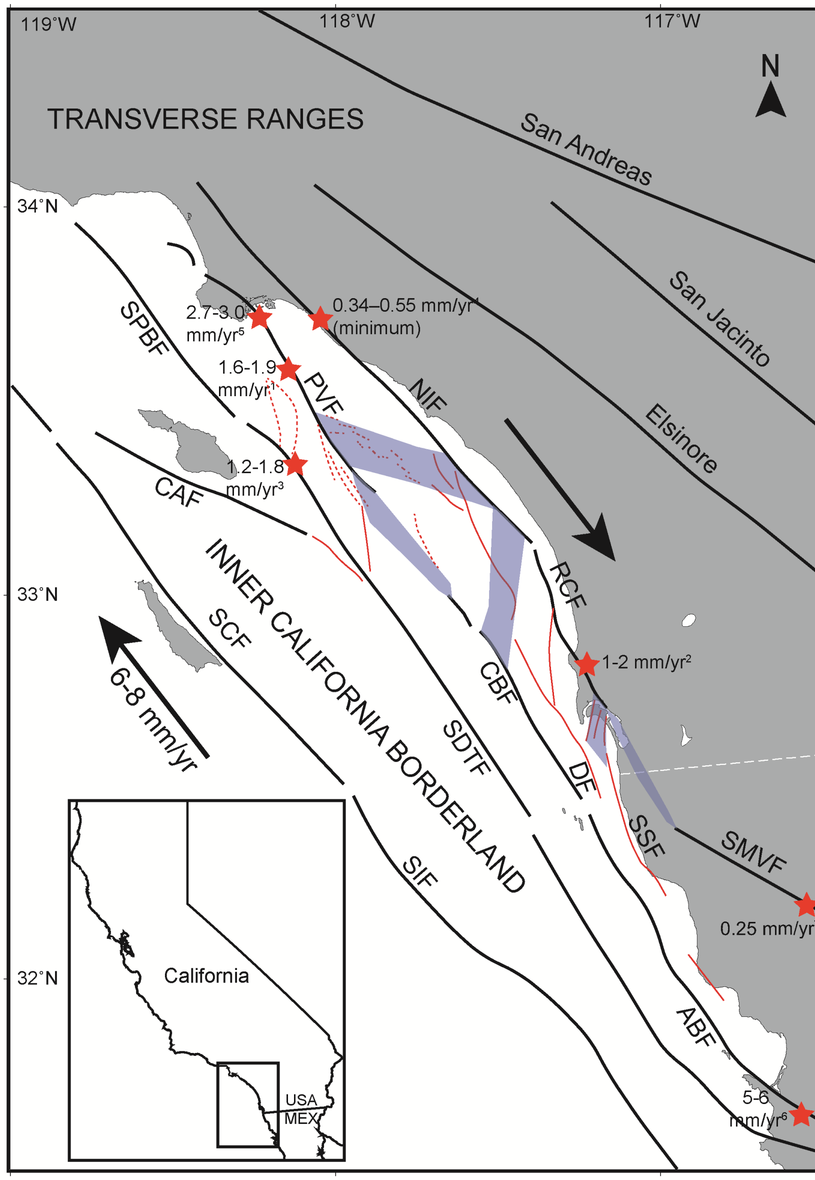

Fig. 7: Generalized map of ICB strike slip fault systems (black) with red stars showing locations where geologic slip rates have been determined. There are no slip rate estimates for Outer Borderland fault systems. Red lines show more detailed fault zones from recent mapping efforts (Brothers et al., 2015; Conrad et al., 2018; Sorlien et al., 2015). Blue polygons show potential regions of slip transfer between faults as discussed in the text. NIF – Newport Inglewood fault, RCF – Rose Canyon fault, DF – Descanso fault, SMVF – San Miguel Vallecitos fault, ABF – Agua Blanca fault, PVF – Palos Verdes fault, CBF – Coronado Bank fault, SPBF –San Pedro Basin fault , SDTF – San Diego Trough fault, SSF – Silver Strand fault, CAF – Catalina Island fault, SCF – San Clemente fault, SIF – San Isidro fault. Slip Rate sources: 1. Brothers et al., 2015; 2. Lindvall and Rockwell, 1992; 3. Ryan et al., 2012; 4. Grant et al., 1997; 5. McNeilan et al., 1996; 6. Rockwell et al., 1993; 7. Hirabayashi et al., 1996.

The slip rate on the Palos Verdes fault also appears to decrease moving to the south from Long Beach. Although the Palos Verdes fault zone is along strike of the Coronado Bank fault zone to the south, new evidence suggests a dying out of the Palos Verdes fault to the south and the potential transfer of slip from the NI-RC fault onto the Palos Verdes fault zone (Fig. 7) (Brothers et al., 2015; Ryan et al., 2009). Farther south on the NI-RC, there is also evidence for transfer of slip from the Coronado Bank fault to the NI-RC across a series of faults that were recently mapped in detail (Sorlien et al., 2015; Conrad et al., 2018). However, there are no slip rate estimates for the Coronado Bank fault to compare with the Palos Verdes and NI-RC slip rates that might help to resolve these linkages.

Still farther south along the NI-RC, a step across San Diego Bay offers two potential pathways for transfer of slip (Figs 6 & 7): 1. The Descanso fault offshore San Diego bay, which trends south offshore Baja, Mexico and then links up with the Agua Blanca fault system onshore, and 2. The San Miguel-Vallecitos fault, which trends more northwesterly across the northern Baja peninsula. Both faults have been suggested to transfer slip across the San Diego bay step-over onto the Rose Canyon fault, but a clear linkage has not been identified (Moore and Kennedy, 1975; Hirabayashi et al., 1996; Trieman, 1993; Dixon et al., 2002).

In addition to the scarcity of slip rates, there is also a dearth of paleoseismic data for faults in the CCB. As such, the recurrence intervals, dates of most recent events, event size, and pre-historic rupture patterns are unknown. Within the NI-RC fault zone, the onshore paleoseismic records in San Diego and Orange County have been used to infer a potential northward cascading series of earthquakes (Grant and Rockwell, 2002; Singleton et al., 2019), but the gap in event timing for the offshore segments leaves this question unresolved (Fig. 6).

Unique Opportunities

Detailed fault structure

Faults in the CCB are highly complex, with bends and step-overs, anastomosing strands, and interactions between high- and low-angle fault systems. Although similar structures may be located in the onshore portion of the P-NA plate boundary, the location of the CCB offshore allows for very

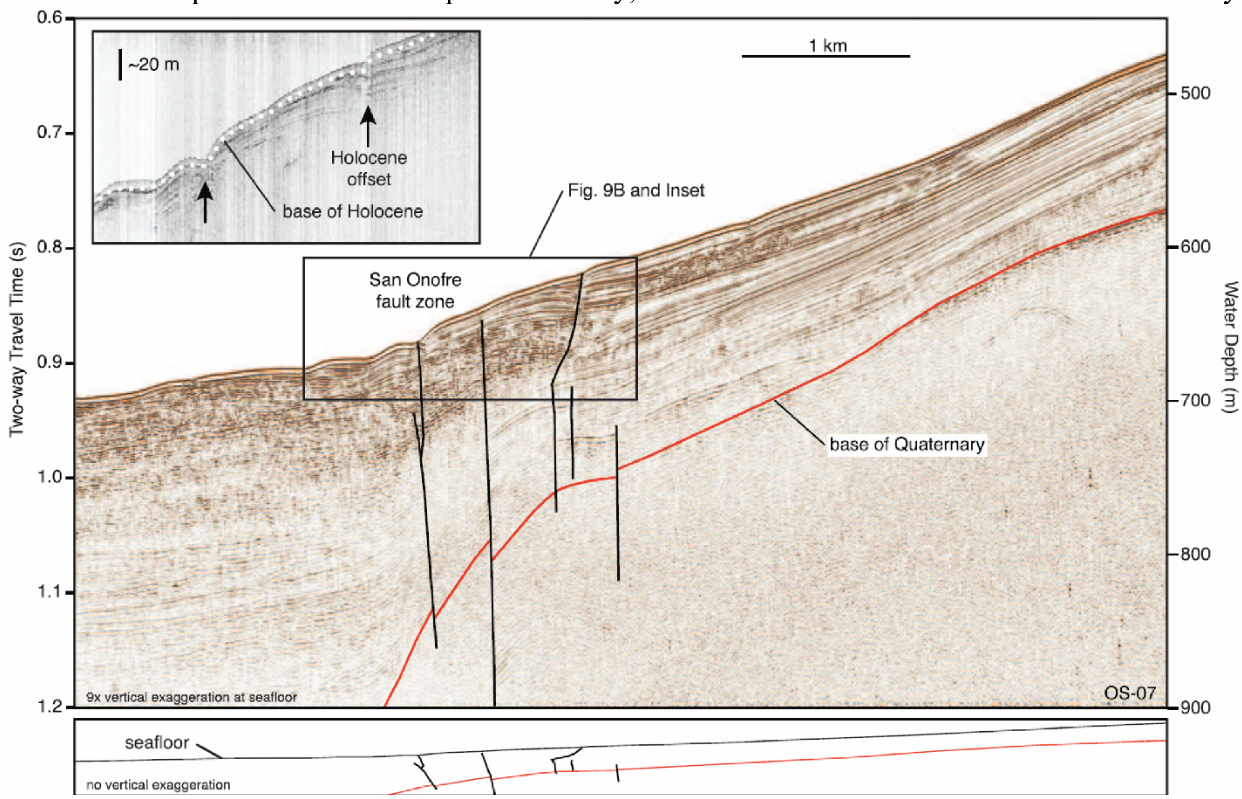

Fig. 8: Figure from Conrad et al. (2018) showing combined deeper penetration seismic reflection data (sparker) combined with very high resolution seismic Chirp data (inset) to interpret fault zone geometry and recency of faulting. Seismic reflection profiles are located across the San Onofre fault zone. Faults in black, base of Quaternary horizon in red, base of Holocene in white dots. Vertical exaggeration approximately 9:1 at seafloor. Interpretation shown with no vertical exaggeration in lower panel.

detailed mapping over large areas using shipboard seismic reflection methods. By combining data with different seismic sources, fault zones can be imaged near the surface at decimeter vertical scale, and down to several kilometers at lower resolutions that define deeper structure and stratigraphy (Fig. 8). Many of these data already exist in the CCB and reprocessing with modern techniques has been shown to improve data quality (Maloney et al., 2016). 3D seismic data can also provide highly detailed images of the complex structure across fault segment boundaries, which is important for understanding the role these boundaries play in rupture initiation and termination. High-resolution bathymetry can also image deformation features at the seafloor. These data are similar to onshore LiDAR, but the CCB seafloor is not complicated by vegetation or large scale human-built structures.

Stratigraphic Framework

In addition to imaging structures, seismic reflection data can provide a stratigraphic framework to interpret deformational history. Erosion characterizes much of the onshore region of southern California, but the CCB is a region of deposition, so a more complete record of plate boundary deformation and fault interaction is preserved, as well as a dated syntectonic stratigraphy that can help document dates and rates of active crustal deformation. This may be particularly important at fault bends and steps, which would be better preserved in offshore stratigraphy compared to the more erosional onshore environment.

Variable data points for rupture modeling

There are differences between the onshore and offshore regions of southern California that are important for models of earthquake processes across the P-NA plate boundary. The CCB has experienced a different tectonic history over the last 30 Ma, resulting in different patterns of crustal structures. The NI-RC represents a boundary between the Peninsular Ranges basement to the east and the Catalina Schist to the west, as well as a transition from thicker crust onshore to thinner crust in the Inner Borderland (ten Brink et al., 2000; Nazareth and Clayton, 2003; Lekic et al., 2011). The CCB has undergone periods of subduction, oblique extension, vertical-axis block rotation, and translation resulting in complex structures that likely influence crustal deformation and earthquake processes. The region may also have undergone a period of nascent seafloor spreading (Legg, 1991) and there is some evidence for a lower crustal layer of subducted oceanic crust (Miller, 2002). A better understanding of 3D crustal structure is important for reconstruction of the P-NA plate boundary evolution and provides vital data for models of earthquake rupture and seismic wave propagation.

The CCB also differs from the onshore environment in that its faults are located under hundreds of meters of seawater, meaning pore fluids and pore fluid pressures will differ from those onshore. The pressure induced by increasing the water column over a fault zone has been shown to potentially influence earthquake processes (Brothers et al., 2011, 2013) and the CCB has undergone several Quaternary sea-level cycles with the coastal fault zone (NI-RC) alternating between submerged and subaerial surface exposure. Furthermore, previous and recent discoveries of methane seeps in the CCB offer an opportunity to investigate the poorly understood relationship between seismic activity and fluid expulsion. Several of the newly discovered seeps are located at restraining bends and steps along major CCB strike-slip fault systems (Conrad et al., 2018b; Lonsdale, 1979; Maloney et al., 2015; Paull et al., 2008; Torres et al., 2002), which could elucidate spatial and temporal patterns of fluid migration at segment boundaries and their relationship to seismicity.

Path Forward

There are several mechanisms to advance research on faulting and earthquakes in the CCB and incorporate this important region into the SCEC natural laboratory:

1. Seismic reflection data

Higher density and improved quality seismic reflection and bathymetric data are important for mapping fault structures and related syntectonic stratigraphy, identifying which faults are active, quantifying slip rates, and determining paleoseismic history. 3D data across segment boundaries would provide detailed fault geometry at these important locations that would otherwise be difficult to obtain onshore. Very high-resolution data collected from AUVs and ROVs are a proven method for determining horizontal slip rates on deep water fault systems (Ryan et al., 2012; Brothers et al., 2015). Currently, only two such slip rate estimates exist in the CCB. Estimates of slip rates for other CCB fault systems are urgently needed. Similar investigations using seismic reflection data could also help resolve paleoseismic history through indirect evidence from earthquake triggered event deposits (e.g., Navy Fan; Legg et al., 2007; Goldfinger, 2011; Maloney et al., 2013), or where a component of vertical offset records multiple events in cross section (e.g., Pondard and Barnes, 2010; Brothers et al., 2009), potentially at releasing bends or steps. In all cases, high-resolution geophysical data need to be accompanied by sediment coring to provide age controls on observed deformation.

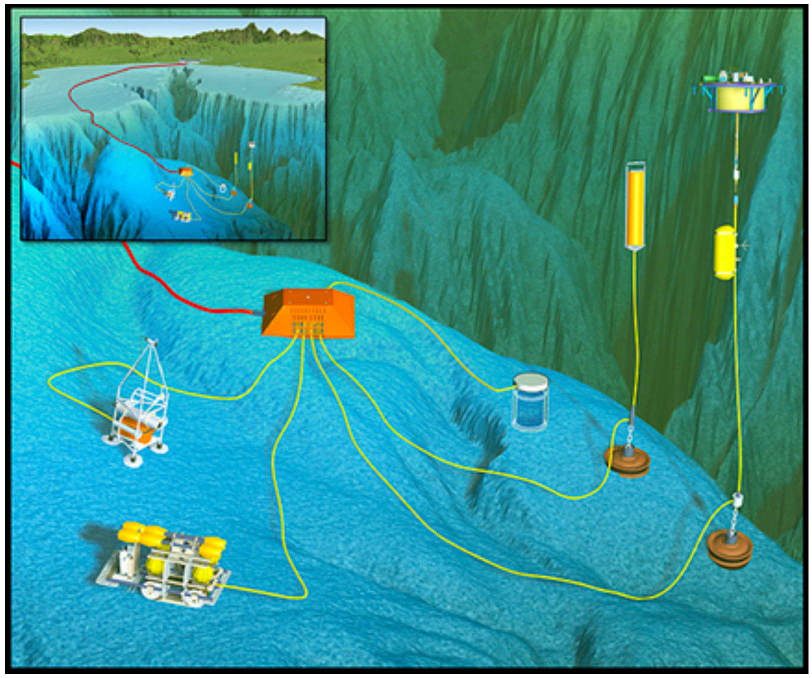

Fig. 9: The Monterey Accelerated Research System (MARS) is located on the seafloor 891 meters below the surface of Monterey Bay. The main MARS node (orange box with sloping sides) connects to shore through a 52-km-long power and fiber-optic cable. MARS serves as an engineering, science, and education test bed for even larger regional ocean observatories. (https://www.mbari.org/at-sea/cabled-observatory/)

2. Offshore infrastructure

There are now several seafloor observatories around the world where an array of instruments is deployed and data are fed back to shore through fiber-optic cables (e.g., VENUS – Salish Sea, British Columbia; Cambridge Bay, Arctic Ocean; MARS – Monterey Bay, CA) (Fig. 9). These observatories are instrumented with tools valuable to a wide variety of disciplines including marine biology, physical oceanography, and earth science. The MARS observatory includes geodetic and seismic sensors, as well as hydrophones, which recently recorded the October 17, 2019, M4.7 earthquake from the San Francisco Bay area. Such instrumentation is lacking in the CCB, but could be a huge step forward in understanding offshore earthquake processes. Such a system could be a joint effort between SCEC and other agencies interested in offshore processes (e.g., NOAA, U.S. Navy, Scripps Institution of Oceanography). Additionally, fiber-optic cables themselves can provide data on seismicity (Mestayer et al., 2011; Lindsey et al., 2019) and opportunities exist to utilize such data from existing cable systems across the CCB.

Given the complex crustal structure in the CCB, deployment of additional seismometers on offshore islands and ocean-bottom seismometers (OBS) across the CCB would provide data to determine accurate 3D seismic velocity structure offshore and more accurate/precise location of seismicity and depth of faulting. A permanent OBS array could be deployed in critical locations where data are most lacking (e.g., Outer Continental Borderland, San Clemente Island fault zone). Seafloor GPS instrumentation has also recently been developed that could be deployed long-term across the CCB to determine geodetic slip across offshore fault zones (Bürgmann and Chadwell, 2014; Bartlow et al., 2019).

3. Onshore-offshore efforts

Within the CCB, the coastal fault zone (including the NI-RC) stands out both for its potential hazard, being located closest to the coastline and trending onshore into major metropolitan areas, and for its potential opportunities to learn about earthquake processes in the region. The entire coastal fault zone extends from the Agua Blanca fault onshore in Baja, Mexico, north along the Baja coastline as the Descanso and Silver Strand fault zones, and then onto the Rose Canyon and Newport Inglewood fault zones to the north (Fig. 6). Along this length, the fault zone steps on and offshore in numerous places, including a large releasing step-over at San Diego Bay (Figs. 6 & 7). Work along the coastal fault zone could take advantage of the benefits of both onshore and offshore fault investigations. One potential focus site is near the mouth of the Santa Ana River, where the principal displacement zone of the NI fault zone shifts eastward from offshore at Newport Beach to onshore at Huntington Beach (Fig. 6). The complex zone of faulting displays evidence of transtension in shallow geologic structure and signifies potential Earthquake Gate characteristics if the 1933 Long Beach earthquake stopped at this location. Earthquake rupture processes may be also affected by variable fluid pressures in the overstep. This step occurs right at the coastline where onshore and offshore efforts could be combined to map 3D structure that can be incorporated into dynamic rupture models. Farther south, a coastal fault that may link with the Silver Strand fault to the north steps onshore at Punta Salsipuedes, Baja (Fig. 6), where a road cut exposes offset stratigraphy that could be used to reconstruct a paleoseismic record for this segment of the coastal fault system for comparison with records to the north and south. Additional studies on the fault zones in northern Baja and offshore in areas where paleoseismic data are missing (Fig. 6) would fill important gaps in our current understanding of the coastal fault zone. Furthermore, interactions between high- and low-angle faults occur near the coast, so onshore-offshore seismic imaging projects could be critical to properly resolving the nature and geometry of this fault interaction.

4. Seismicity patterns

Improved earthquake locations through the use of new methods, or improved offshore infrastructure would also open the CCB to more research on spatial and temporal seismicity patterns. These types of studies could lead to identification of repeating events or possible precursory activity to larger events. The 1986 Oceanside earthquake is an interesting event that occurred at a restraining step on the San Diego Trough fault and included numerous fore and aftershocks (3215 events from 1981 to 1997; Astiz and Shearer, 2002) across a 15-20 km wide vertical zone of activity (Hauksson et al., 2012; Legg et al. 2015). This step is also characterized by high- and low-angle faults and an active methane gas seep at the seafloor (Maloney et al., 2015), offering an opportunity to investigate a fault segment boundary that was the site of rupture initiation, interesting seismicity patterns, fault interactions, and the relationship between active fluid seepage and seismicity. Additionally, the Outer Borderland region exhibits evidence of on-going seismic activity (Legg et al., 2015), including the 2012 M6.3 earthquake within the oceanic lithosphere west of the Patton Escarpment (Hauksson et al., 2014), and the 2018 M5.3 earthquake near Santa Rosa Ridge, but seismicity patterns have only been initially explored. Additional instrumentation, as discussed previously, would enhance understanding of ongoing seismicity across the CCB.

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