Technical Report:

Evolution of the San Diego Bay Pull-Apart Basin

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Proposal Category:
B: Integration and Theory
SCEC Transitions Program

SCEC Priorities addressed: P3.a, P3.e, P5.b

Project Objectives:

The principle objective of this project was to assess the pull-apart basin evolution and potential connectivity of regional fault systems around San Diego Bay, CA. This project focused on faulting in the southern portion of San Diego Bay where several northwest oriented faults were imaged outside the 'active' pull-apart basin. The data used in this project include legacy multi-channel seismic (MCS) lines, borehole logs and age models, and high-resolution chirp data. The MCS and borehole data were collected as part of the geohazard study of the Coronado bridge in the late 1990s, and high-resolution chirp data were collected in 2011-2013, and 2019. Using these datasets, our goals were to generate a detailed fault map and cross sections in San Diego Bay, and assess the spatial and temporal changes in stratigraphic sequences throughout the Bay. We planned to use these products to better understand potential rupture pathways and resolve changes in the evolution of the San Diego Bay pull-apart.

Methodology:

The MCS data used in this study were collected as part of a seismic hazard assessment of the Coronado bride in the mid-1990s (Kennedy and Clarke, 1996). The original survey collected 130 km lines of MCS, 250 km lines of single channel boomer data, and a transect of boreholes beneath the Coronado bridge (Kennedy and Clark, 1996; 1999). Unfortunately, all of the original computer data (stored on magnetic tape files), were destroyed in a warehouse fire before they could be transferred to modern digital format, this included the original navigation files. Thus, the only surviving copies of the seismic data were thought to be working paper copies (owned by the original investigators) and the figures included in the final report filed with the City of San Diego and the California Division of Mines and Geology (Kennedy and Clark, 1996). However, a spring-cleaning effort at the offices of the US Geological Survey-Menlo Park unearthed a set of the original magnetic tape copies of the MSC lines collected in San Diego Bay. These lines were transferred to modern digital format and reprocessed through the Shearwater Revel software package (Revel, 2019).

Working with collaborators at the USGS Santa Cruz Pacific Coastal and Marine Science Center we applied a processing scheme to increase the resolution of the MCS data. The processing flow we applied is as follows:

- Linear moveout and f-k filtering
- Water bottom mute
- Common mid-point stacking with normal moveout correction + velocity semblance
- Brute stacking
- Time migration

Reprocessing the older MCS data with improved computational techniques dramatically increased the resolution at depth allowing for better characterization of fault

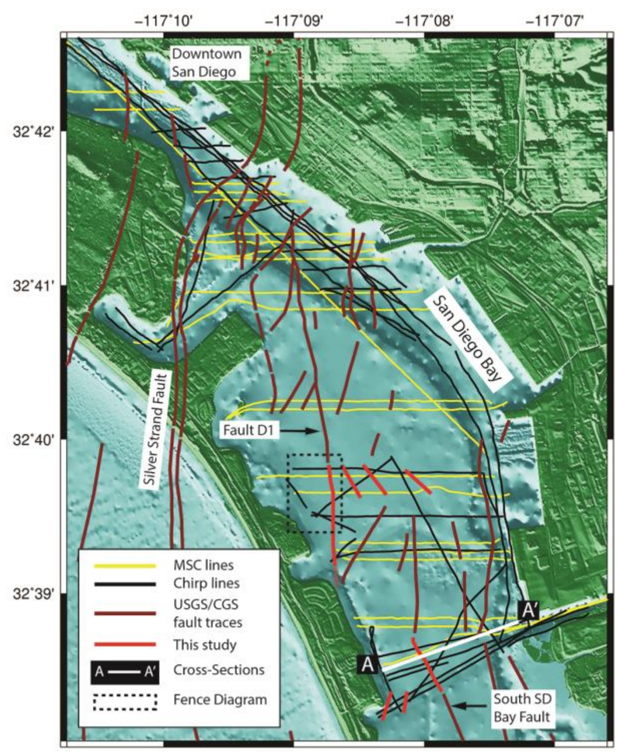

Figure 1) Map of the study area showing geophysical survey lines, previously mapped faults from the USGS/CGS quaternary fold and fault database (USGS, 2019), and faults mapped through this project.

geometry and stratigraphy. The magnetic tapes did not include navigation for the MCS lines, so the locations had to be digitized from the figures included in the original report. First the figures were georeferenced in ArcGIS and the individual MCS lines were digitized. The total length of the digitized line was divided into equal spaced ‘shots’ at 3.125 m spacing, which is the shot spacing of the original acquisition (Kennedy and Clarke, 1996). Due to uncertainties in the digitization of the original figure, the final locations likely carry a location error of ~10-12 m. Borehole data were extracted from a cross-section collected beneath the Coronado Bridge and include age constraints (radiocarbon, amino acid stratigraphy, and paleontological analysis) on underlying strata (Kennedy and Clarke, 1999). During 2011-2013, and 2019 high-resolution seismic reflection data were collected in San Diego Bay using Scripps Institution of Oceanography’s Edgetech chirp profiler, operated with a 50 ms swept pulse of 1-15 kHz and 0.7-3.0 kHz, providing sub-meter vertical resolution with sub-bottom penetration up to ~50 m, and location accuracy within 5 m. Chirp data were processed using sioseis and Seismic Unix. Both the MCS and chirp data were interpreted using IHS Kingdom Suite to examine changes in stratigraphy and fault geometry.

Results:

San Diego Bay is an area of extensive faulting with previously mapped short, discontinuous segments located in its southern portion (Figure 1) (USGS, 2019; Kennedy and Clarke, 1996). These segments generally trend north-northwest and exhibit a down to the east sense of displacement (Kennedy and Clarke, 1996; Kennedy and Moore, 1975). The reprocessed MCS data resulted in good-quality, usable data down to ~450 ms, and imaged many of the fault segments previously mapped in the study area (Figure 2). The processed chirp data resulted in high-resolution seismic images down to ~ 50 ms (~40 m assuming a

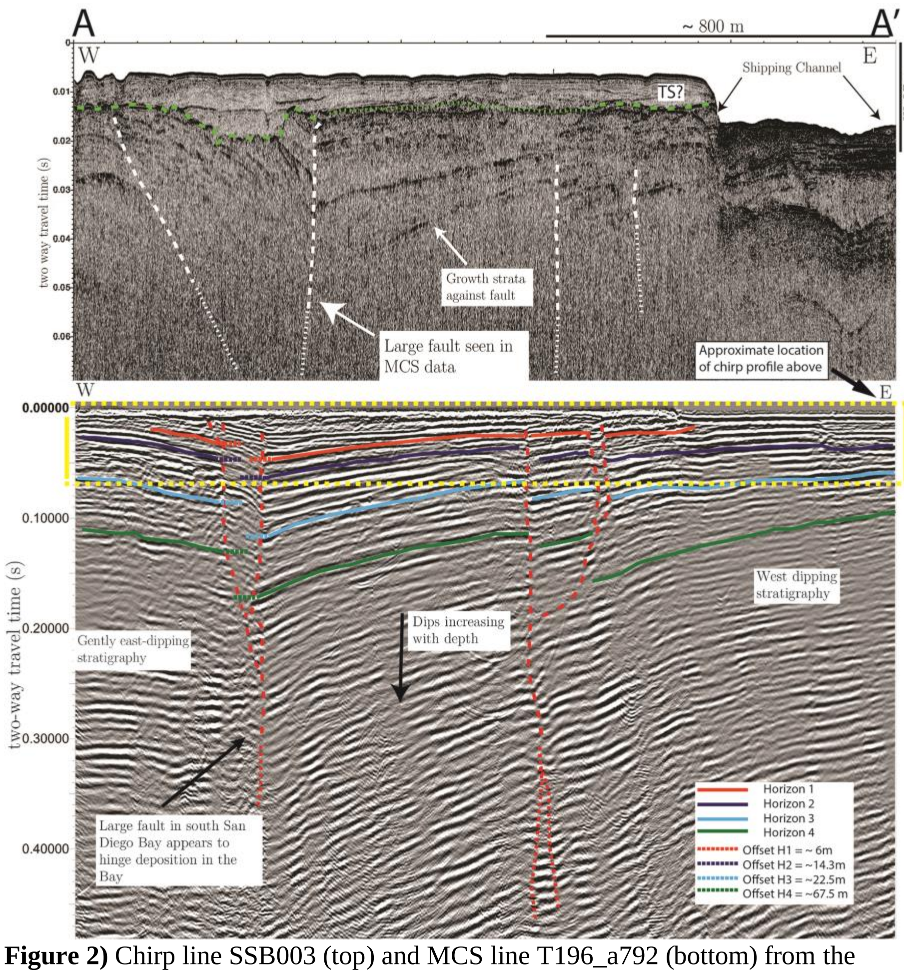

Figure 2) Chirp line SSB003 (top) and MCS line T196_a792 (bottom) from the southern portion of San Diego Bay (see figure 1 for location of A-A’). The south San Diego Bay fault is well imaged in both the Chirp and MCS data in the western part of the profiles. The increasing stratigraphic dips with depth and growth strata observed in the chirp data show the faults effect on deposition in this part of the Bay. TS=Transgressive Surface, shown as green dashed line.

velocity of 1500 m/s). By combining the MCS and chirp datasets we have extended the traces of several of the most prominent faults seen in the southern bay (Figure 1). This mapping shows that several of the previous short discontinuous segments are part of larger faults that control the location of a depositional basin in the southern portion of Bay (Figures 1 and 3).

The 'south San Diego Bay fault' is a large fault in the southern-most portion of the study area (Figures 1 and 2). The fault exhibits a down to the east sense of displacement and develops into a negative flower structure towards the surface (Figure 2). The MCS data show progressively increasing offsets and stratigraphic dips with depth associated with the south San Diego Bay fault (Figure 2). Additionally, growth strata terminating against the fault are also imaged in the high-resolution chirp data (Figure 2). Observed down to the east offsets across this fault include, an offset of ~ 6 m for horizon 1 (H1), an offset of ~14.3 m for horizon 2 (H2), an offset of ~22.5 m for horizon 3 (H3), and an offset of ~67.5 m for horizon 4 (H4) (Figure 2). The character and geometry of the south San Diego Bay fault is variable along strike; in the south displacement is concentrated onto a single fault (Figure 2), as the fault trends northward deformation is distributed onto a series of sub-parallel fault strands that continue to have down to the east sense of motion (Figure 1). The south San Diego Bay fault may offset a reflector with a similar character and geometry to what has been interpreted as the transgressive surface at other locations in San Diego Bay (Figure 2) (Maloney, 2013). Additionally, a high amplitude reflector terminates directly above where the south San Diego Bay fault intersects the potential transgressive surface (Figure 2).

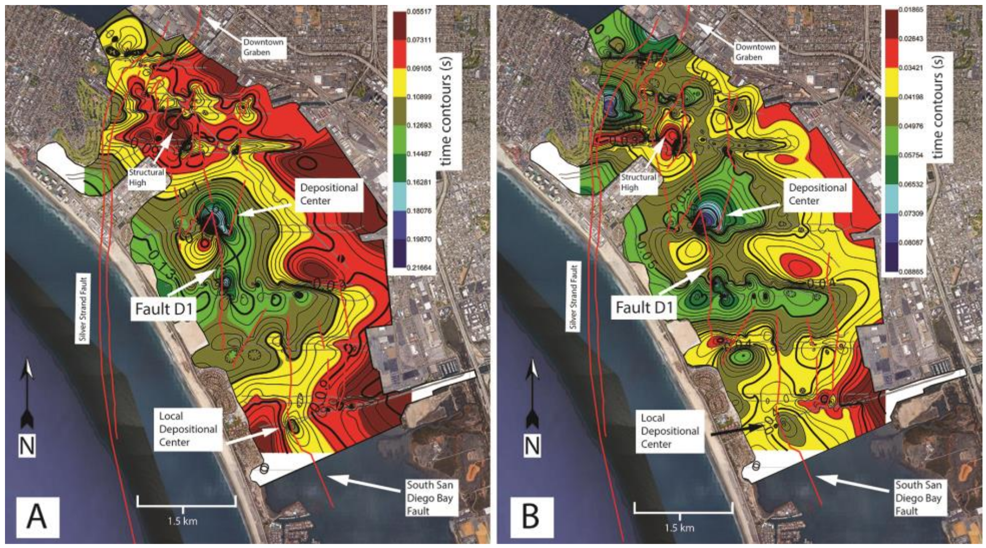

Figure 3) A) Gridded surface of horizon 3. B) Gridded isopach of unit 2 bounded by horizon 2 and horizon 3. See figure 2 for horizon 2 and 3 relative position.

In the western portion of the study area, the combined MCS and chirp datasets show a continuation of the previously mapped D1 fault from Kennedy and Clarke (1996). We extend its trace south towards the Silver Strand (Figures 1 and 4). As noted by Kennedy and Clarke (1996), fault D1 is a major fault in San Diego Bay that trends southward from an intersection with the Silver Strand fault adjacent to downtown San Diego. The fault exhibits a down to the east sense of motion for its entire trace, and increasing stratigraphic dips and progressively larger offsets with depth are also observed along D1 in the MCS data. However, unlike the south San Diego Bay fault, D1 appears to have its greatest amount of offset along its northern segment and diminishes southward (Figure 3). Faulting associated with D1 is also mostly distributed with several closely spaced strands acting together to accomplish the down to the east sense of motion. Fault D1 appears to control the pathway of Chollas Creek, which is diverted southward upon contact with the fault trace and follows the fault towards the Silver Strand (Figure 4). Potential recency of faulting for D1 is difficult to establish due to the shallow location of the first multiple reflection occurring at a similar depth to the interpreted transgressive surface; however, radiocarbon dates from beneath the Coronado Bridge indicate that this fault is Holocene active (Kennedy and Clarke, 1999). For both the south San Diego Bay fault and fault D1, faulting is seen to become more distributed near the edge of the stepover with the Rose Canyon fault, with an increase in sub-parallel strands observed near the intersection of the south bay faults and the Silver Strand fault.

With no tie-lines collected in the study area during the original MCS survey, we relied on several distinctive stratigraphic sequences to correlate stratigraphy between survey lines that were spaced on average ~400 m apart in the southern portion of the bay. Four distinctive high-amplitude reflectors separated packages of more chaotic to homogenous low-amplitude packages, and were used to separate the stratigraphy into three main units. These four horizons, shown in Figure 2, were mapped across the study area to observe changes in stratigraphic character. Using IHS Kingdom Suite software, gridded surfaces of the mapped horizons and isopach maps were generated for improved visualization (Figure 3). Due to the geometry of the original MCS survey, occasional large (~800 m) areas of the gridded surfaces are without data to constrain the interpolation.

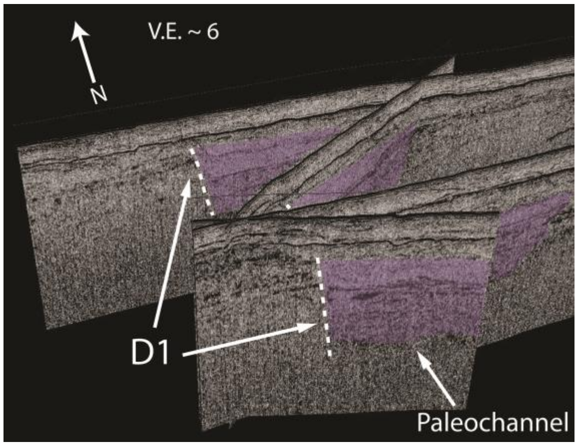

Figure 4) Fence diagram of chirp lines from the northern portion of the study area showing the trace of D1 and its controlling influence on Chollas Creek (purple). See figure 1 for location.

The stratigraphy of the study area generally dips towards the west and show one primary basin or depositional center adjacent to fault D1 (Figure 3). The horizon 3 gridded surface shows that this area of subsidence reaches its greatest depth in the northern portion of the study area (Figure 3). An isopach map of unit 2 (which is bounded by horizons 2 and 3) confirms that this area contains the thickest stratigraphic sequence (Figure 3). In the southern portion of the study area, a localized region of subsidence is observed as a result of motion on the south San Diego Bay fault (Figure 2, and 3). In addition to these two basins, several smaller localized depositional centers are mapped in the gridded surfaces (Figure 3).

At the northern portion of the study area, there is a complex interaction occurring between the Silver Strand fault, fault D1, and the faults of the Downtown Graben. The horizon 3 surface reaches its greatest depth (~160 m) just south of the intersection and adjacent to fault D1, while adjacent to this basin is a large structural high where the horizon 3 surface is at ~50 m depth (Figures 1 and 3). Amino acid stratigraphy and paleontological analysis of material collected adjacent to pier 18 of the Coronado Bridge suggests mid-Pleistocene deposits at a depth of at least ~140 m. The large vertical changes associated with the Silver Strand fault did not facilitate the correlation of horizons across the fault, but this will be a focus of future work.

Significance:

Our results show that reprocessed legacy MCS data is a valuable tool available to the earthquake science community for studying fault characteristics in areas where data collection may now be difficult due to regulation or anthropogenic modification. Our reprocessing efforts resulted in improved resolution at depth and allowed for better delineation of stratigraphic packages and fault geometries. The improved picture of the deeper fault structure in San Diego Bay was correlated with faulting observed in the shallow subsurface using high-resolution chirp data, and has resulted in an improved understanding of the active faults beneath San Diego Bay.

San Diego Bay has been interpreted as a pull-apart basin formed by a right step-over between the dextral Descanso and Rose Canyon faults (e.g., Legg, 1991; Rockwell, 2010; Maloney, 2013). However, observations such as variable faulting at the tips of the master strike-slip segments and extensive faulting outside of the active basin, suggest that the classical pull-apart basin model may not fully explain the fault geometry beneath San Diego Bay. Some studies have suggested additional connections to other regional faults such as the San Miguel-Vallecitos fault (Maloney, 2013; Kennedy and Clarke, 1996; Tremain, 1993). The total step from the Descanso fault to the Rose Canyon fault is >10 km, so a through-going rupture is not predicted; however, a potential stepover from the Rose Canyon fault to the San Miguel-Vallecitos fault could be on the order of ~3-4 km, a distance historical ruptures have jumped (Wesnousky, 2006). Additionally, rupture models show that the presence of smaller faults within a step-over can have a complicated effect on rupture propagation across a step, as well as evolving stepover geometry that may result in variable slip (Lozos et al., 2015; Wakabayashi et al., 2004; Wu et al., 2009). Therefore, the study area in south San Diego Bay was chosen because of the presence of faults outside of the Rose Canyon fault-Descanso fault stepover that could provide a possible linking fault geometry for a connection to the San Miguel-Vallecitos fault and the potential to observe changes in stratigraphic character.

In the south of the study area, the growth strata imaged in the chirp data (Figure 2) indicates that the faults in south San Diego bay (particularly the south San Diego Bay fault) are controlling deposition in this portion of the basin. Based on correlation of age data from the Coronado Bridge boreholes, this deformation has been occurring from at least the late-Pleistocene and possibly as early as the mid-Pleistocene. If the irregular reflector imaged in the chirp data represents the transgressive surface, this deformation may be continuing into the Holocene (Figure 2). South of the study area, the south San Diego Bay fault may narrow into a more concentrated zone where gravity data indicate a basin low (Marshall, 1989). Northward the shorter distributed sub-parallel segments may represent connecting rely faults between larger faults, such as the south San Diego Bay fault and the D1 fault. These shorter northwesterly and northeasterly trending faults in between the D1 and south San Diego Bay faults could help accommodate motion between segments of the nested San Diego Graben (Figure 1) (Marshall, 1989).

The apparent structural high observed in the stratigraphy beneath the central portion of San Diego Bay is a result of a complex interaction between the major faults in the Bay (Figure 3). This location is near the edge of the San Diego Bay pull-apart where the Silver Strand fault, D1 fault, and the faults of the Downtown Graben consolidate motion just south of the main Rose Canyon Fault strand; how slip is partitioned through this area is still uncertain (Weidman et al., 2019). The subsidence observed in the southern portion of San Diego Bay suggest that relatively recent subsidence has been occurring outside of the Descanso-Rose Canyon fault stepover and may indicate additional influence of other regional faults such as the San Miguel-Vallecitos, in the down-dropping of San Diego Bay. Future work will focus on comparing the basin geometry with pull-apart basin models to determine which model best explains the development of San Diego Bay given the orientations and activity of the regional fault systems.

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