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UNIVERSITY OF CALIFORNIA, SAN DIEGO

**Architecture and Segmentation of Strike-Slip Faults in Southern
California**

A dissertation submitted in partial satisfaction of the
requirements for the degree
Doctor of Philosophy

in

Earth Sciences

by

Valerie Jean Sahakian

Committee in charge:

Neal William Driscoll, Co-Chair
Alistair Harding, Co-Chair
Jose Ignacio Restrepo
David Thomas Sandwell
Lisa Tauxe

2015

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The dissertation of Valerie Jean Sahakian is approved,
and it is acceptable in quality and form for publication
on microfilm and electronically:

Co-Chair

Co-Chair

University of California, San Diego

2015

DEDICATION

To my family, and to Nanny, who I think would be very proud of the “puzzles” I have moved on to solve as I have grown.

EPIGRAPH

*Standing on a hill in my mountain of dreams; Telling myself it's not as hard, hard,
hard as it seems*

— *Led Zeppelin*, Going to California

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I must thank my labmates, past and present, for the fun times, foosball games, and for sharing a wide breadth of knowledge. Science is certainly not accomplished alone, and you have all been great partners.

I have made many friends here at Scripps. My cohort (Robert, Diego, Samer, and Fernando) have been my family away from home. Our discussions and jokes over chalkboard problems, coffee, and beer have been instrumental in who I’ve grown to be in my time here. There are many people who have entered my life at some point here, and who have made this place my home – Soli, Lana, Janine, Ashlee, Janin, Geoff, Mike, Alain, GP students, and many many others – Scripps is Scripps because of the wonderful people you meet, and school would not have been the same without you.

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According to Neal: “It only gets worse”. While this may sound a bit disheartening to a wide-eyed and bushy-tailed student, I have to say that my starting baseline, before and during graduate school, has been pretty high – I think “worse” will be just fine.

The work in this dissertation is in the submission process. Chapter 2 can be found in:

- Kell, A. M., **Sahakian, V.J.**, Kent, G. M., Driscoll, N. W., Harding, A. J., Baskin, R. L., Barth, M., Hole, J. A., Stock, J. M., and Fuis, G. S., “New Constraints on the Architecture and Evolution of the Imperial-San Andreas Pull-Apart System Beneath the Salton Sea, California”, *submitted to Geosphere*

Chapter 3 in:

- **Sahakian, V.J.**, Kell, A. M., Harding, A. J., Driscoll, N. W., Kent, G. M., “Geophysical Evidence for a San Andreas Fault Splay in the Salton Sea”, *submitted to co-authors*

and Chapter 4:

- **Sahakian, V. J.**, Bormann, J. M., Driscoll, N. W., Harding, A. J., Kent, G. M., Wesnousky, S., “Newport Inglewood Rose Canyon Fault Segmentation: Implications for Rupture Propagation”, *submitted to co-authors*

I give great thanks to my co-authors on these publications. I have learned a lot from them throughout the process, and it has been a pleasure to work with them.

VITA

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Sahakian, V. J., Bormann, J. M., Driscoll, N. W., Harding, A. J., Kent, G. M., Wesnousky, S., “Newport Inglewood Rose Canyon Fault Segmentation: Implications for Rupture Propagation”, *submitted to co-authors*

Sahakian, V.J., Kell, A. M., Harding, A. J., Driscoll, N. W., Kent, G. M., “Geophysical Evidence for a San Andreas Fault Splay in the Salton Sea”, *submitted to co-authors*

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Lindsey, E. O., **Sahakian, V. J.**, Fialko, Y., Bock, Y. Barbot, S., and Rockwell, T. K., “Interseismic Strain Localization in the San Jacinto Fault Zone”, *Pure and applied geophysics*, 171(11), 2014

ABSTRACT OF THE DISSERTATION

**Architecture and Segmentation of Strike-Slip Faults in Southern
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by

Valerie Jean Sahakian

Doctor of Philosophy in Earth Sciences

University of California, San Diego, 2015

Neal William Driscoll, Co-Chair

Alistair Harding, Co-Chair

This dissertation investigates the architecture and segmentation of fault structures in Southern California, using marine active-source seismic data. Off-shore or marine fault geometry is often poorly constrained due to their location. This study employs marine active-source seismic data to image these structures, and further the current understanding of the hazards they pose to the region.

With these data, this dissertation first improves the existing framework of knowledge of fault architecture in the Salton pull-apart basin, near the terminus of the Southern San Andreas Fault (SSAF). It investigates the evolution of the pull-apart basin in the Imperial-San Andreas fault system with reflection and re-

fraction data, and provides important constraints regarding the interplay of faults and strain partitioning in this region. New data suggest the existence of a previously unknown fault in the Salton Sea, the Salton Trough Fault (STF). This transtensional fault is located just to the west of the eastern Salton Sea shoreline, and strikes approximately parallel to the SSAF terminus.

Finally, this dissertation investigates the architecture and segmentation of the Newport-Inglewood/Rose Canyon (NIRC) fault zone offshore Southern California, using seismic data sets with unprecedented density and resolution. It identifies four main fault strands, with three main stepover boundaries, and presents possible rupture scenarios based on quantitative and qualitative assessments of throughgoing rupture at stepovers or segment boundaries.

Chapter 1

Introduction

Straddling the Pacific/North American plate boundary, California Earthquake Country is at high risk of experiencing a large earthquake. Past earthquakes in the region have proven to be very destructive in terms of lives lost and economically. Large and devastating earthquakes in the past century include the 1906 San Francisco earthquake, the 1971 San Fernando earthquake, the Imperial Valley earthquakes of 1940 and 1979, and, more recently, the 1989 Loma Prieta, the 1994 Northridge, and the 2010 El Mayor events.

Estimated as a M_w 7.8 (*Ellsworth, 1990*), the 1906 San Francisco earthquake is currently ranked as one of the most significant earthquakes of all time. It ruptured 430 km of the San Andreas Fault, from San Juan Batista to its northern termination at the Cape Mendocino triple junction. Monetary damage was equivalent to \$10.5 billion in 2015, and the death toll from the earthquake and subsequent fire was reported at 700; however, the death toll is believed to be 3 to 4 times greater than reported (*Ellsworth, 1990*). The M_w 6.7 1994 Northridge earthquake is one of Americas most costly disasters, with economic losses close to \$20 billion dollars. Occurring in the San Fernando Valley, this event caused severe damage to infrastructure, nevertheless the death toll of 60 was considered relatively low (*U S Geological Survey (USGS), 1996*), with more than 7,000 injured. Additionally, the earthquake triggered many ground failures and landslides (*U S Geological Survey (USGS), 1996*). The M_w 7.2 El Mayor earthquake originated in Baja California, Mexico and inflicted a lower death toll than the Northridge

earthquake; however, agricultural infrastructure was significantly damaged, and there was some structural damage to buildings in both the US and in Mexico.

Improving our understanding of seismic hazards increases our chances of being more prepared for such large events, and thus mitigating loss of life and damage to infrastructure for future large earthquakes. There are a number of parameters that affect seismic hazard and its assessment, including earthquake history (i.e., recurrence interval), fault slip rates, site effects, fault geometry, location, and segmentation. Estimates of these values control predictions of the potential magnitudes and locations of future events, which in turn, inform models of ground shaking. Fault segmentation often plays a significant role in earthquake magnitude. Traditionally, guidelines and hypotheses that underpin predictions of total rupture length rely solely on surface-based observations, and do not consider fault dip and strike at segment boundaries, i.e., *Wesnowsky* (2006), or are based on 2D models of throughgoing rupture (*Lozos et al.*, 2011). A combination of both qualitative and quantitative methods, of both observation and modeling, can improve our understanding of the likelihood of a rupture propagating through an observed stepover or segment boundary. Additionally, it is difficult to make predictions about future earthquakes if the kinematics of a fault zone and the location of fault splays are unknown or poorly constrained. These two topics are key components of the scientific questions posed and investigated in this thesis.

Active-source seismic imaging is used in all of the following chapters and studies to constrain fault location, segmentation, and style of deformation on several fault systems in Southern California. These data together with other data types provide important constraints required to assess seismic hazard. For example, trenching studies may aid in resolving earthquake history and fault slip rates; geodesy provides insight into fault slip rate as well as location. Seismicity often provides suggestions regarding fault location and structure at depth, and constraints on local and regional velocity structure and site effects. Seismic imaging, geologic observation, and recorded historic events yield information on fault location, recurrence interval, and segmentation.

Until 30 Mya, the US Western coast was an active convergent margin, as the

Farallon plate subducted beneath the North American plate (*Atwater and Stock, 1998; McQuarrie and Wernicke, 2005; Nicholson et al., 1994*). Subduction ceased offshore Los Angeles, as the hot and buoyant East Pacific Rise (EPR) approached the trench, beginning between the Murray and Pioneer fracture zones, and migrating north and south. The margin transitioned from a convergent to transform boundary and accommodated the plate motion between the North American plate and the Pacific plate. This process initiated transform motion in the continental lithosphere between 5 and 30 Mya, eventually forming the strike-slip fault structures and San Andreas Fault system found in California today (*Atwater and Stock, 1998; McQuarrie and Wernicke, 2005*). Concurrently, rifting in the Gulf of California (GoC) migrated north. The Salton pull-apart basin, between the Imperial and San Andreas fault systems, is the youngest and northernmost area of GoC rifting.

Today, there is approximately 50 mm/yr of slip between the Pacific plate at San Clemente Island, and the North American plate through the Eastern California Shear Zone (ECSZ) (*Bennett et al., 1996*). This is partitioned onto a number of fault systems, onshore and offshore. At the latitude of San Clemente Island, the main onshore fault zones are the San Andreas Fault (SAF), San Jacinto Fault (SJF), Elsinore Fault (EF), and the offshore faults include the Newport-Inglewood/Rose Canyon (NIRC) fault, San Mateo/Carlsbad (SMC) trend, Coronado Bank (CBF), Palos Verdes (PVF), San Diego Trough (SDTF), San Pedro Basin (SPBF), and San Clemente (SCF) faults. Figure 1.1 shows a summary of these systems, from *Grant and Shearer (2004)*. The majority of the slip rate is partitioned on the onshore faults, with the SAF accommodating 18 – 25 mm/yr of slip (*Fay and Humphreys, 2005; Fialko, 2006; Lundgren et al., 2009*), however the SJF accommodates 9 – 19 mm/yr of slip (*Bennett et al., 1996; Fialko, 2006; Lindsey et al., 2014*), the EF approximately 4 – 6 mm/yr (*Bennett et al., 1996; Lindsey et al., 2014*). Offshore, slip rates are more challenging to constrain due to the lack of geodetic, or geologic data. After removing the slip rates observed on the onshore faults, approximately 5 – 8 mm/yr remain for all of the offshore faults between San Clemente Island and the coast. Paleoseismic studies have con-

cluded that the NIRC accommodates approximately $0.5 - 2$ mm/yr, depending on location, and the PVF approximately 3 mm/yr (Bennett *et al.*, 1996; Grant and Shearer, 2004; Lindvall and Rockwell, 1995; Rockwell, 2010).

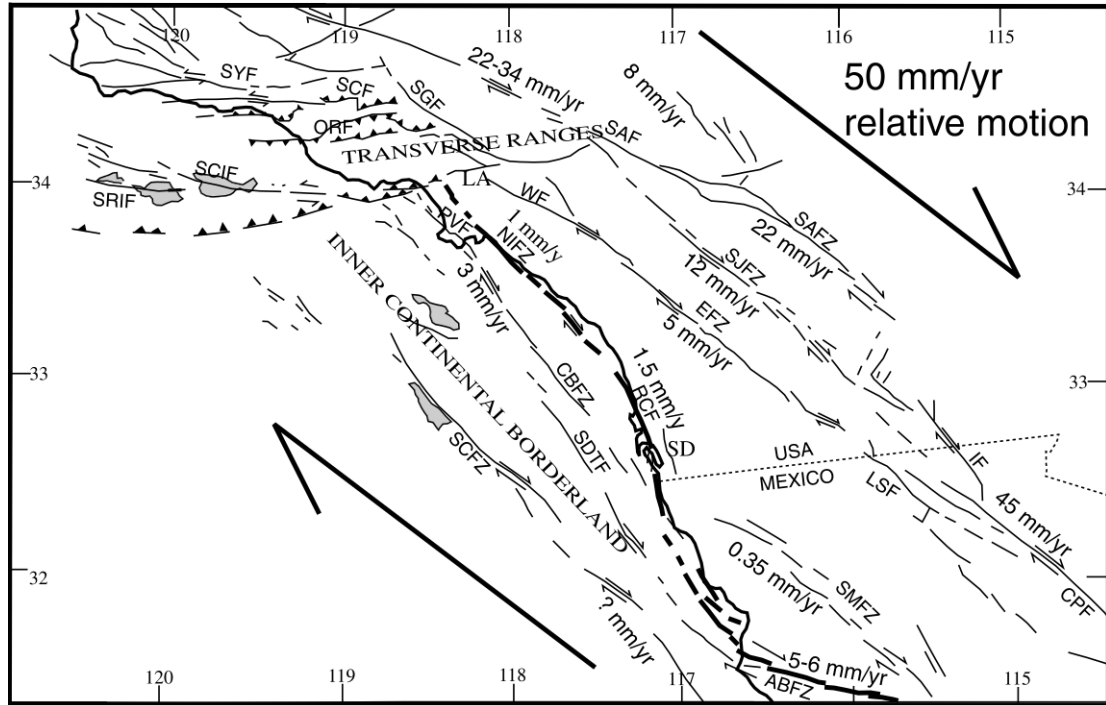
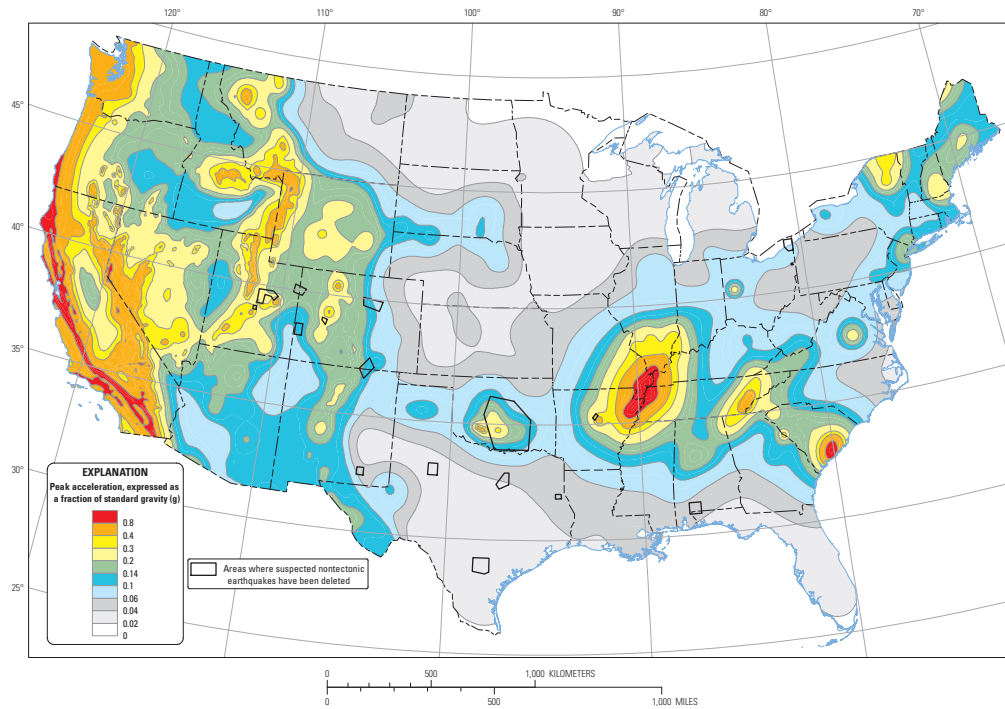


Figure 1.1: Map of major faults in Southern California, and their estimated slip rates. From Grant and Shearer (2004). San Andreas fault (SAF), San Jacinto fault zone (SJFZ), Elsinore fault zone (EFZ), Whittier fault (WF), Palos Verdes fault (PVF), NIFZ near Los Angeles (LA), RCF zone (RCFZ) near San Diego (SD), Agua Blanca fault zone (ABFZ), San Miguel fault zone (SMFZ), Imperial fault (IF), Cerro Prieto fault (CPF), and Laguna Salada fault (LSF). Offshore faults of the inner Continental Borderland include the Coronado Bank fault zone (CBF), San Diego Trough fault (SDTF), San Clemente fault zone (SCFZ), Santa Cruz Island fault (SCIF), and Santa Rosa Island fault (SRIF). The San Gabriel fault (SGF), San Cayetano fault (SCF), Oak Ridge fault (ORF), and Santa Ynez fault (SYF) are located in the Transverse Ranges.

According to the USGS national seismic hazard maps, the SAF and SJF are the faults expected to produce the highest peak ground acceleration (PGA) in Southern California, reaching almost $1g$ (Figure 1.2). These maps show the two-percent probability of exceeding certain PGAs in the next 50 years, and are dependent on a number of factors. Two of these are the maximum potential mag-

nitude of an earthquake on that fault determined from magnitude scaling relations from fault area or length constraints, and the location of known faults (*Petersen et al.*, 2014). It is therefore critical to accurately predict the maximum length of rupture, and consequently, determine the likelihood of throughgoing rupture in a highly segmented fault system. This dissertation focuses on two main regions of faulting in Southern California: the Southern San Andreas Fault (SSAF), and the Newport-Inglewood/Rose Canyon (NIRC) fault zone. The results of these studies have the potential to alter and improve the source assumptions mentioned above that drive these hazard models and maps.



Two-percent probability of exceedance in 50 years map of peak ground acceleration

Figure 1.2: USGS Hazard map of the two-percent probability of exceeding a PGA in 50 years in the United States. The color bar of PGA is on the bottom left of the figure.

The first two chapters investigate the structure and tectonic evolution of the SSAF system and Salton pull-apart basin. The SSAF has the potential to generate

a large earthquake, and depending on rupture direction, could induce strong and sustained ground shaking in the Los Angeles basin, or the Imperial Valley and Mexicali regions (*Olsen et al.*, 2006). Constraining the regional architecture as well as shallow crustal velocity structure will not only improve the current models of ground-shaking, but will also further our understanding of the evolution of the pull-apart basin and migration of GoC rifting for application to other pull-apart basins and segment boundaries around the world. Chapter 2 (*Kell, Sahakian et al., submitted to co-authors*) (*Kell et al.*, 2016) investigates the regional structure and tectonic evolution of the Salton Trough and Salton pull-apart basin, and Chapter 3 (*Sahakian et al., submitted to co-authors*) (*Sahakian et al.*, 2016b) delves further into the local structure of the SSAF adjacent to the Salton Sea, and describes the discovery of a fault parallel to the SSAF in the Salton Sea. These new data have significant implications for segment triggering and event magnitude that should be considered in future community fault model revisions and scenario ruptures.

Chapter 4 moves offshore, to characterize the architecture and segmentation of the NIRC fault zone. Except for the 1933 Long Beach earthquake (M_w 6.4), the Newport-Inglewood fault has been seismically quiet, and the offshore NIRC has not experienced a seismic event in historic times. The UCERF3 fault model (*Field et al.*, 2014) describes the onshore Newport-Inglewood fault, offshore Newport-Inglewood fault, and offshore Rose Canyon fault as separate segments that are not likely to rupture together in the same event. Similarly, the USGS national seismic hazard maps (*Petersen et al.*, 2014) describe the NIRC fault zone as producing lower PGA in the coastal regions. These assigned hazards may change with denser imaging data and subsequent analysis, as shown in Chapter 4 (*Sahakian et al., submitted to co-authors*) (*Sahakian et al.*, 2016a). They are particularly important to understand, as an earthquake on this fault system could affect the densely populated coastal regions of San Diego, Orange, and Los Angeles counties (the most densely populated regions in Southern California), as well as Tijuana in northern Baja California.

Throughout the course of the inquiries presented in the following chapters using marine active-source seismic data, advances have been made not only in

understanding the hazards presented by these fault systems, but also how active tectonics affect local and regional geomorphology and margin architecture. The findings present new and important constraints on local tectonic evolution, as well as provide parameters for future inputs to hazard determinations.

Chapter 2

New Constraints on the Architecture and Evolution of the Imperial – San Andreas pull-apart system beneath the Salton Sea, California

2.1 Introduction

2.1.1 Tectonic Setting

The Imperial – San Andreas pull-apart system is the northernmost component of the oblique rift system that initiated in the Gulf of California (GOC) through a series of right-stepping dextral faults, which have migrated north throughout rift development (*Atwater and Stock, 1998*). The transition from the GOC proper into the heavily sedimented Colorado deltaic system of northern Baja California and southern California (*Dorsey, 2010*) is highlighted by a transform boundary controlled by relatively long dextral faults offset by small pull-apart spreading basins; this dispersed right-lateral system terminates into the through-going strike-slip plate boundary of the Southern San Andreas fault (SSAF). The modern Salton

Sea and prehistoric flooding of Lake Cahuilla (*Waters, 1983; Philibosian et al., 2011*) are located in the sub-sea-level region (forming an endorheic basin containing water at depths below ~ 71 m relative to global sea level) within the Imperial – San Andreas pull-apart system, and is the northernmost pull-apart basin of the GOC rift system. Near the northern termination of the GOC rift system, the two previously identified dextral faults are the Imperial fault to the southwest and the SSSAF to the northeast (IF, SSSAF - Fig. 2.1). In addition, seismic data suggest the existence of a new fault along the eastern shoreline of the Salton Sea (STF – Fig. 2.1). Ongoing studies of pull-apart basins in the GOC show the complexity of segmented faulting within the basins, highlighting how one strike-slip fault transitions into another and the role strain partitioning plays in the timing and style of deformation (e.g., *Persaud et al. (2003), Wesnousky (2005)*). The Salton Sea presents an ideal opportunity to study pull-apart basin complexity. Seismic reflection data image the structural and stratigraphic architecture from within the active pull-apart system (i.e., normal hinge faults first identified in *Brothers et al. (2009)*) as well as the basin-bounding strike-slip faults that step over, forming the pull-apart. We approach the understanding of these complexities through the use of marine seismic techniques, combined with a detailed stratigraphic record from ancient Lake Cahuilla.

The Salton Trough (darker gray pattern in Figure 2.1) is a low-lying basin that extends from the northern GOC to San Gorgonio Pass encompassing the Cerro Prieto basin and the Salton Sea pull-apart system. The series of faults forming the GOC rift and the Salton Trough are part of the Southern San Andreas Fault system (SSAF, *Persaud et al. (2003)*), accommodating oblique-divergent plate motion with distributed extension across northeast-southwest striking normal faults. The Salton Trough was initially more extensional and through time east or west-dipping low-angle detachment faults such as the West Salton Detachment fault evolved, in a system that runs from the northern end of the Salton Trough to northern Baja California (*Axen et al., 1999; Dorsey, 2010*). It is estimated that subsidence began in Late Miocene. Recent studies suggest that slip on the West Salton detachment fault may have ceased near 1 - 2 Ma, coeval with the initiation of

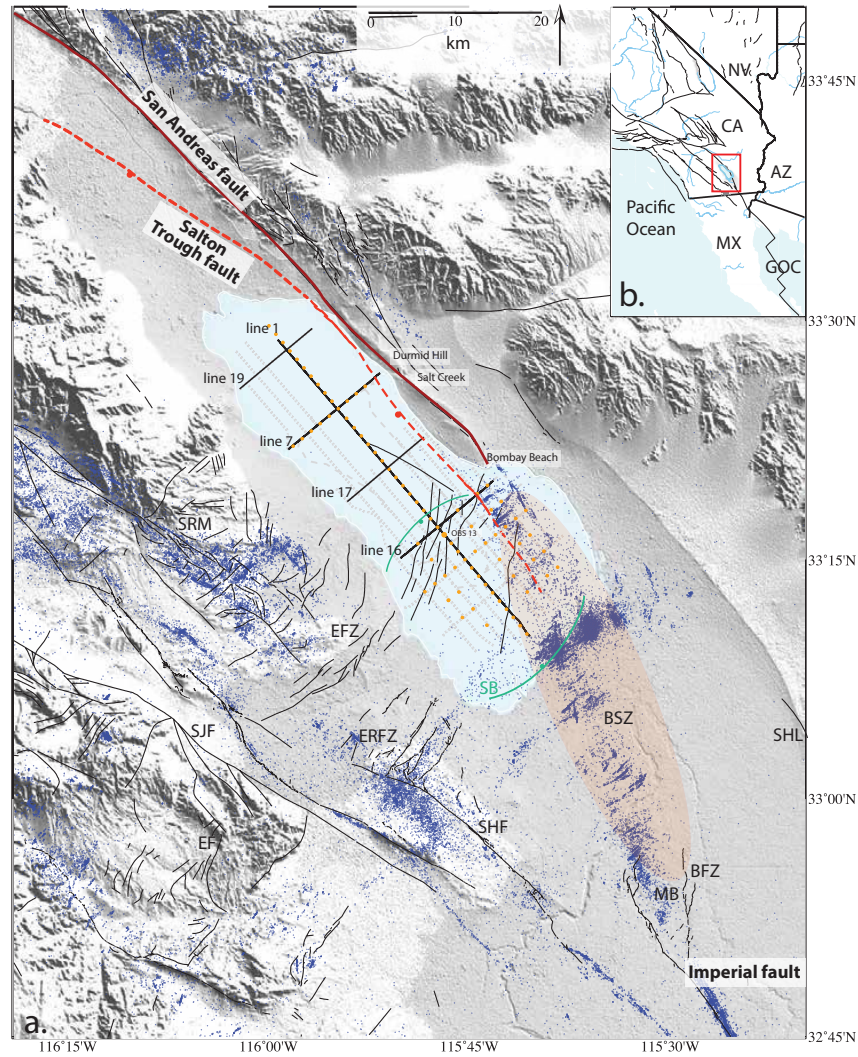


Figure 2.1: Map of Salton Sea. (a) Dark black lines show MCS reflection profiles shown in Figures 3-8 and red dots highlight the location of the OBS array (OBS site 13 is highlighted). Other profiles acquired in the 2010 campaign are shown as short-gray dashed lines, while the longer dashed lines are additional profiles collected in 2011. Purple dots highlight relocated earthquakes (Hauksson et al., 2012). The location of the newly inferred Salton Trough strike-slip fault with down to the southwest component is shown. Abbreviations: BF, Brawley Fault, BSZ, Brawley Seismic Zone; IF, Imperial Fault; MB, Mesquite Basin; SB, Salton Basin; SHL, Sand Hills Lineament; EFZ, Extra Fault Zone; EF, Elsinore Fault; SJF, San Jacinto Fault; ERFZ, Elmore Ranch Fault Zone; SRM, Santa Rosa Mountain. (b) regional map showing the location of the study area in Southern California.

dextral strike-slip motion on the San Jacinto fault (*Kirby et al.*, 2007; *Steely et al.*, 2009), although the recent El Mayor-Cucapah earthquake also involved low-angle normal faulting (*Fletcher et al.*, 2014). Recent extension in the Salton Sea area (*Brothers et al.*, 2009) is oriented along a NW – SE direction in the southern Salton Sea. Throughout the Pliocene into the Pleistocene, the subsided area served as a catchment basin for the Colorado River and has received extremely high inputs of Colorado River sediments beginning in the late Miocene (~ 6 Ma) when the river was first diverted into the low lying Salton Trough and northern Gulf of California (*Dorsey et al.*, 2007). Thick sedimentary sections and their thermal blanketing effect likely influenced styles of tectonic deformation and volcanism by changing the rheology of the lithosphere (*Dorsey*, 2010). Late Pleistocene and Holocene sediments also provide chronologic control on slip-rates on faulting and current tectonic configuration (*Kirby et al.*, 2007).

Moving northward from the GOC, the Cerro Prieto Fault (CPF) forms the Cerro Prieto pull-apart system as it steps over onto the IF (*Suarez-Vidal et al.*, 2008). This geometry is mimicked once again where the IF steps over onto the Brawley Fault Zone (BFZ) through the Brawley Seismic Zone (BSZ) forming the Mesquite sub-basin and then onto the SSAF, forming the Salton sub-basin (SB). Studies of the Mesquite sub-basin and IF provide constraints on the ages of these structures: *Fuis* (1998) seismically determined a crystalline basement (thermally altered sediment) depth of ~ 4 -6 km; using a sedimentation rate of 4-8 mm/yr from *Meltzner et al.* (2006), we calculate the Mesquite sedimentary basin to be between 500 k.y. and 1.5 m.y. B.P. *Larsen and Reilinger* (1991) conclude that the Mesquite Basin and the northern portion of the Imperial Fault is much younger than the larger Imperial fault, providing an upper age limit of ~ 100 k.y. The youthful structures along the southern shore of the Salton Sea are attributed to the concentration of recent volcanism (*Elders et al.*, 1972). Additionally, CHIRP data acquired by *Brothers et al.* (2009) in the Salton Sea revealed a pull-apart basin bounded by northeast-southwest striking normal faults consistent with model predictions for pull-apart basin development (e.g., *Elders et al.* (1972); *Mann et al.* (1983)).

Long-term questions arise regarding the SSAF along its southernmost reaches (south of Bombay Beach Figure 2.1) and the role of the STF that is subparallel to the SSAF. Does the southernmost segment of the SSAF partition strain onto the STF while it dies away in response to the northward propagation of the IF? In turn, what roles do the BSZ and STF play in this evolution? The present day geometry and trench excavations (*Meltzner et al.*, 2006) suggest that the BFZ is youthful in comparison to the IF and SSAF, and may owe its existence to a dying SSAF, with the formation of the Mesquite and Salton sub-basins recording its inception.

2.1.2 Seismic Studies

Within the marine setting of the Salton Sea, a nesting of seismic reflection data of differing resolutions, including two multi-channel seismic (MCS) campaigns (sparker and G.I. gun sources) and a series of ocean bottom seismometer (OBS) deployments provide new insights into the development of pull-apart basin systems, including the northward evolution or propagation of this dynamic system. The latest deep penetration (up to 3-5 km) seismic studies offer insight into the history of basin structure that were not resolved by the mid- to late-Holocene record observed in the seismic CHIRP data (*Brothers et al.*, 2009). To this end, the Salton Sea allows the use of marine seismic applications with high data density and a nested range of vertical resolution to analyze the tectonic history recorded by the stratigraphic horizons. Seismic images within the pull-apart basin itself, as well as along the outer segments of the basin where step-over and extension is initiated, give a detailed history of tectonic activity. The combination of near surface data at high-resolutions and deeper penetrating seismic reflection images that approach seismogenic depths, allows analysis of the tectonic evolution over the last ~ 150 k.y. B.P. and likely over an even greater time span.

2.2 Seismic Methods

Multi-channel seismic (MCS) data were collected in the Salton Sea during the spring of 2010 and 2011. Both field efforts used a Subsea Systems Inc. acquisition system with different configurations to enhance either vertical resolution (2010) or depth of penetration (2011). The high-resolution mode used a 1.6 kJ sparker shot at an ~ 1.3 sec. interval rate and recorded by a 24 channel streamer with hydrophone group spacing at 3.125 m. Shot spacing was comparable to streamer group spacing producing an ~ 12 fold common midpoint (CMP) data. This system was deployed off of a 22 ft. research vessel owned and operated by the USGS; both source and receivers were towed at ~ 3 m below sea surface. The 3-tip sparker system recorded clear arrivals to ~ 1.1 second or a penetration depth of approximately 1 km. This acquisition campaign is shown in Figure 2.1 (short-dashed gray lines). Data processing included velocity analysis along with CMP stacking and predictive deconvolution using 2% prewhitening. These data were also bandpass filtered from 30-200 Hz using SIOSEIS (*Henkart, 2003*). CMP gathering, stacking and deconvolution were performed using in-house modules developed in MATLAB.

The deep acquisition system was tailored to enhance penetration for CMP reflection imaging and ocean bottom seismometer (OBS) refraction recording (Figure 2.2). The source array comprised either a 210 cu. in. or 80 cu. in. generator injector (GI) airgun, towed at a depth between 4-5 m. The data were recorded by 48-channel streamer with a group spacing of 6.25 m, and towed at a depth of 4-5 m. To enhance refraction recording on the OBS array, the airgun shooting interval was every 60 seconds or ~ 150 m. The sparse shot spacing provided only ~ 2 fold for the reflection images. The same processing scheme was applied for these 4-second-long reflection records collected in 2011. Useful reflectivity signals are observed to approximately 4-5 km depth. These low-fold data are shown in Figure 1 (longer-dashed gray lines), and were shot along a subset of the previously collected profiles from 2010 in order to extend the images of fault surfaces to near seismogenic depths.

The 2011 field campaign also deployed 38 different OBSs at 78 unique posi-

tions (red dots shown in Figure 2.1), which recorded during the entire experiment. The OBSs were from the Scripps Ocean-Bottom Seismic Instrument Pool (OBSIP) and were outfitted with hydrophone and Mark Products L-22 3-component, 2 Hz seismometers. The OBS lines were deployed colinear with the major 2010 reflection Lines 1 and 7 in order to complement the high-resolution sparker MCS imagery. An example of an OBS receiver gather for instrument 13 is shown in Figure 2.2; the first arrival picks are highlighted in red (Fig. 2.2, inset).

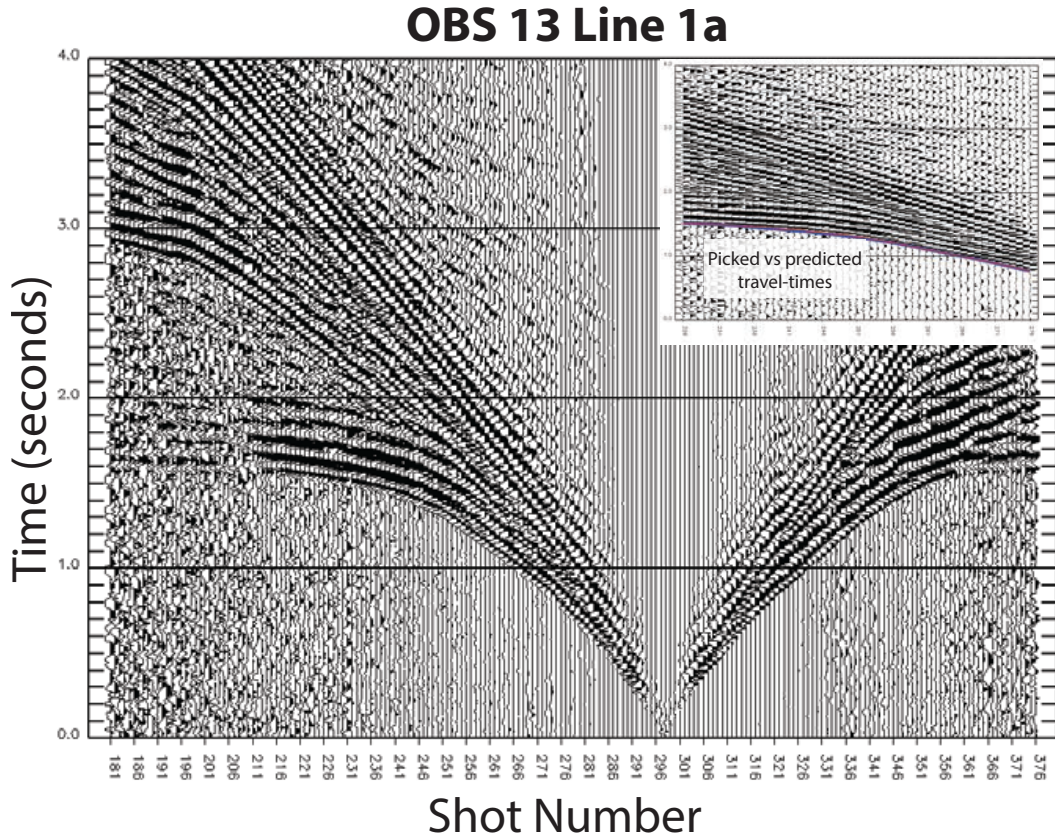


Figure 2.2: OBS Receiver Gather. OBS 13 is located in the southern basin of the Salton Sea. The shot gather shows the p-wave arrivals along with numerous reflections from the underlying stratigraphy. (Inset) Close-up view of P-wave refraction branch with picked (red) and modeled (blue) travel times overlain.

Tomographic methods iterate between first arrival picks from the data and predictions made using raytracing through the most recent velocity model. The traveltimes predictions are shown as a dark blue line (Fig. 2.2, inset) and are up-

dated with each model iteration. Figure 2.3 shows a tomographic inversion of 6754 p-wave arrivals from OBSs along Line 1, created using the methods of *Van Aven- donk et al.* (2004). The model iterates between forward traveltime modeling to fit the data directly and inversion to create an updated, smoothed velocity section. These methods attained a chi-squared fit of 1.67 for the 4.5 km deep model. Picking error varied between 12 ms and 5 ms and was assigned based on the noise level in the picked arrivals.

Additionally, as part of the SSIP project, onshore receivers recorded air-gun sources while onshore explosions were recorded by OBSs (*Rose et al.*, 2013). This study uses only offshore instruments and sources; other research groups involved in the SSIP are analyzing the onshore data.

Swath bathymetry data were acquired in critical regions in the northern and southern Salton Sea using a Simrad 3102 multibeam acquisition system. These 1-m bathymetric grids resolve important seafloor features, although the data were not collected for the entire lake basin. Despite the limited data coverage, the availability of the seafloor bathymetry aided in investigations of previously unrecognized faults on the eastern margin of the Salton Sea. The striped character of the bathymetry data is due to inadequate outerbeam correction due to the abnormally high seawater velocity beyond corrections supported by the software.

2.3 Results and Interpretations

Results from the 2010 and 2011 reflection surveys image structure to depths greater than 1 and 4 km, respectively (Figures 2.3 & 2.4). Though similar in geometry, new data presented here show a much longer time span than the previous high-resolution CHIRP data (*Brothers et al.*, 2009), which recorded to depths <70 m. The 2010 “sparker” data in Figures 4 – 8 provide high resolution images down to ~ 1 km, while the 2011 GI data (Figure 2.3) image stratigraphic relationships to ~ 3 -5 km depths.

The along axis profiles (i.e., parallel to the SSAF and STF) document a young section, above the green horizon, that diverges southeast of a “hinge zone”

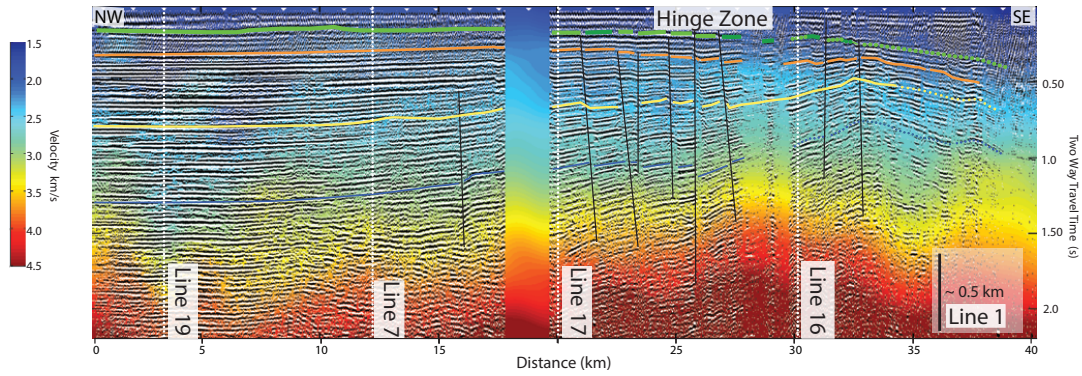


Figure 2.3: Line 1 2011. Multichannel seismic (MCS) reflection profile overlain on top of a 2D P-wave tomographic image from the 2011 air gun survey. Black lines denote the location of normal fault offset along the profile. White triangles along the top of the profile show the locations of OBSs. Colored horizons have been correlated throughout the seismic grid: green horizon shows the onset of vertical divergence above; yellow horizon marks the top of a zone where there is some degree of concordance between stratigraphic layers below; blue horizon depicts the local thinning near the hinge zone. The locations for cross profiles Lines 19, 7, 17, and 16 are shown as white-dotted lines. The tomographic velocity model was converted to TWTT to superpose the velocity data on the CMP data.

(e.g., *Brothers et al. (2009)*). In this section, the stratigraphic layers change from concordant (flat, parallel) layers northward of the hinge zone to divergent (thickening southeastward) layers southward of the hinge zone. An older (deeper) section of sediments (below the orange horizon in Figures 2.3 and 2.4) is faulted and thickens northwestward away from the hinge zone into the northern basin. Thus the younger section and older section show the opposite patterns. The younger section creates a wedge beginning at ~ 0.2 s that thickens to ~ 0.4 s below seafloor, or about 400 m in depth in the southern end of the profile. Tomographic velocity boundaries (Figure 2.3) are consistent with this reflection image; the faulted older section does not appear to thicken to the south. To the northwest end of the along axis profiles, stratigraphic packages are relatively concordant, with little to no lateral thickness variations (little change in thickness between mapped horizons). The layers in the older section are mostly faulted in the hinge zone offshore Bombay Beach (labeled in Figure 2.1), near where the active SSAF terminates into the sea. In this region, we observe a series of northeast striking normal faults (black lines in Figures 2.3

& 2.4) that dip toward the southeast shoreline at dip angles ranging between 55° and 65° . These faults strike $N5^\circ E$ and are approximately 30° - 35° counterclockwise of deeper seismicity lineaments documented in the Brawley Seismic Zone, located in the eastern part of the southern Salton Sea (Figure 2.1).

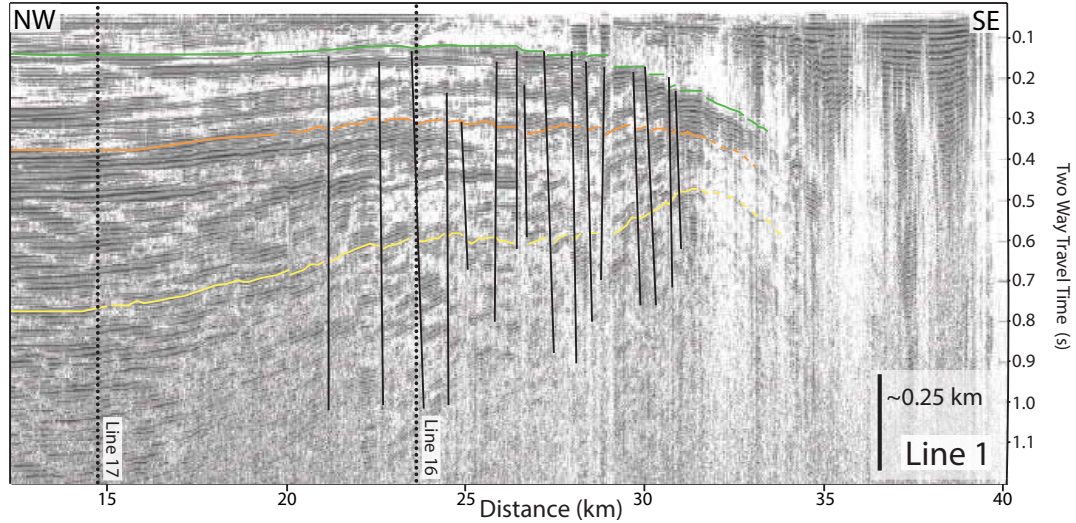


Figure 2.4: Line 1 2010. MCS reflection profile from the 2010 sparker survey. Green horizon shows the onset of vertical deformation and divergence (above), orange and yellow horizons show that divergence near the hinge dies away below 0.5 seconds. Thickening to north suggests that differential subsidence in south was not the dominant signal over time. The location for Line 16 is shown in black dots.

Profiles perpendicular to the SSSAF that include Lines 19, 7, 17 and 16 (from northwest to southeast, Figs. 2.5-2.8) reveal the complex three-dimensional architecture of the Salton Sea near the SSSAF. On Line 7 (Fig. 2.6), in the northern part of the Salton Sea, sedimentary layers thicken toward the northeast, with the dip of the reflectors increasing down-section toward the SSSAF. Stratigraphy near the northeastern edge of Line 7 is folded gently and appears to be truncated beginning at coordinate ~ 13 km (Fig. 2.6). The shallow section from ~ 11 to ~ 14 km shows the presence of gas, though some stratigraphy is visible and may suggest the presence of a SW-dipping fault (Salton Trough fault, STF; interpreted as one of the dashed red lines in Fig. 2.6; see discussion below). The sedimentary layers on Lines 19 and 17, north and south of Line 7 (Figs. 2.5 & 2.7), also dip towards the northeast but show little to no direct evidence of faulting within the Salton

Sea. Onshore observations by *Babcock* (1974) indicate folded, steeply dipping beds for ~ 2 km SW of the SSAF, between the NE ends of our marine Lines and the SSAF.

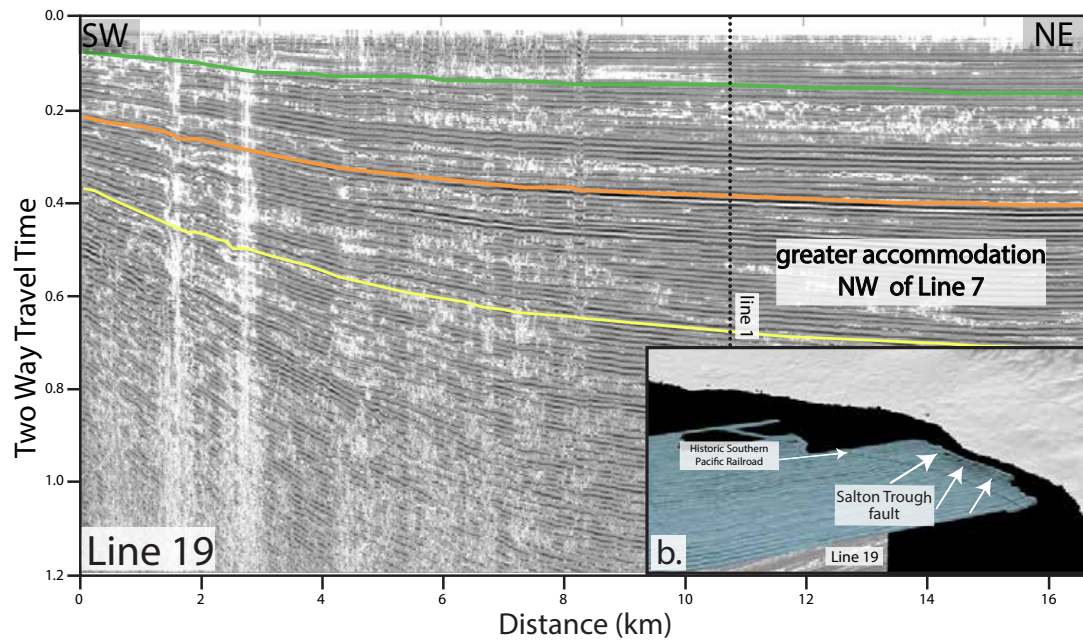


Figure 2.5: Line 19. (a) MCS Line 19 is oriented perpendicular to the SSAF and is located in the northern-most portion of the Salton Sea. This profile shows marked divergence with stratigraphy thickening to the northeast. The divergence is visible to the depth of seismic imaging. See text for discussion of reasons for strata divergence. (b) Simrad 3102 bathymetric map of the northeast section of the sea, highlighting a potential fault scarp associated with the postulated Salton Trough fault; the historic Southern Pacific Railroad that was flooded in 1905 is observed in the swath bathymetry.

In contrast to profiles north of the hinge zone, Line 16 in the southern basin shows reflectors that are slightly folded and faulted with minor down to the northeast offsets between coordinates 8 and 12 km (Fig. 2.8). Line 16 is positioned offshore Bombay Beach in the region adjacent to where the present SSAF dies away into the sea, and where normal NE-striking faults associated with the ‘hinge zone’ intersect the STF (Fig. 2.1). Just east of coordinate 12 km, the sedimentary layers are strongly folded with only minor significantly offset, suggesting a slight component of compression in this region (Figure 2.8). The

strong folding begins at a steeply SW-dipping sharp anticlinal axis (red dashed Line, Fig. 2.8). Unfolding the beds along Line 16 indicates a total of about 5% shortening in the sedimentary section. In addition, the sedimentary package above the green horizon is largely acoustically transparent, and is equivalent to the younger, largely unfaulted sedimentary package observed on Line 1 (Figures 2.3 & 2.4). On both Lines 1 and 16, faults appear to die out within the upper package. In contrast, Line 19 the northernmost Line shows almost no compressional folding but simply eastward fanning dips, as observed on Lines 7 and 17 farther south (Figs. 2.5, 2.6 & 2.7).

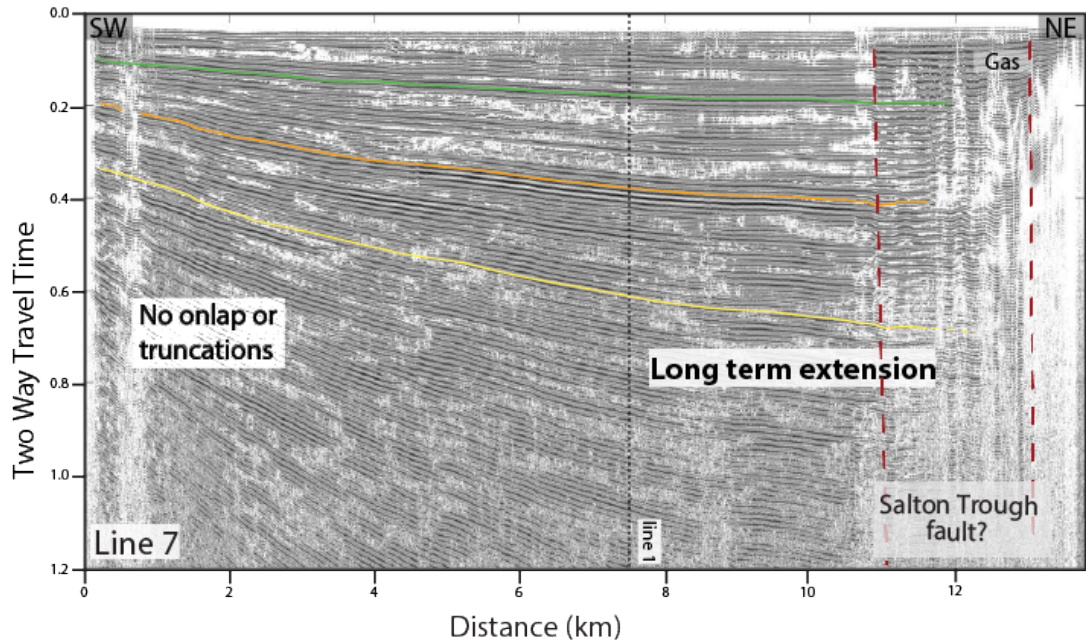


Figure 2.6: Line 7 2010. MCS Line 7 collected in 2010 is perpendicular to the active portion of the SSAF and displays NE-fanning dips. Gas masking is prominent at the NE end of the line. There is uncertainty regarding the potential location of the STF due to gas obscuring reflectors in this region. Two possibilities have been marked by dashed red lines, though it is difficult to form a conclusive interpretation of the STF on this line. Note the stratigraphic dip systematically increases with depth. The colored horizons match in color to horizons in Line 1 and 16. Green horizon marks the cessation of deformation. Orange and yellow display the increasing thickness between layers toward the northeast.

The difference in stratigraphic styles of Line 16 and Line 17 highlights the change from folded stratigraphy along the eastern edge of the pull-apart basin to

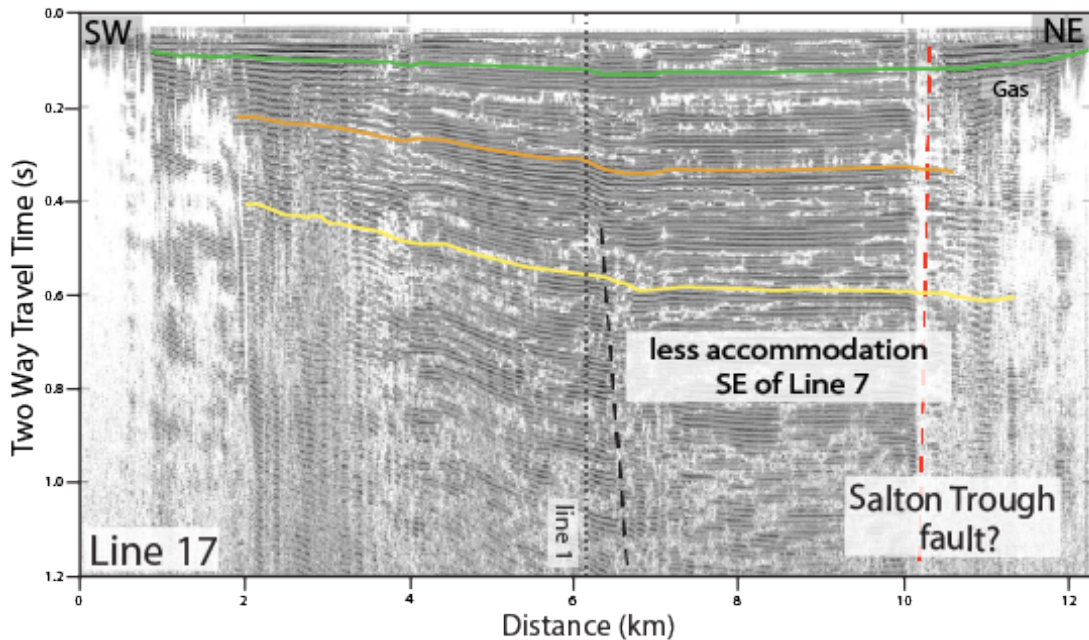


Figure 2.7: Line 17 2010. MCS Line 17 is oriented perpendicular to the SSAF between Lines 16 and 7. Line 17 reveals divergence toward the east, similar to the more northern profiles, although the divergence is somewhat diminished relative to lines to the northwest. The red dashed line indicates the potential location of the STF.

the divergent reflectors dipping to the east (Figs. 2.5 & 2.8). The stratigraphic signatures on Line 17 are transitional between the northern and southern Lines, showing a slight eastern divergence in deeper layers and toward the southwest with more flat lying reflectors northeast of the fault. layering in the shallowmost layers. Lying north of the southern pull-apart basin and attendant hinge zone faulting, Line 17 does not show the dense faulting that occurs in the Salton Sea pull-apart basin (Figures 2.3 and 2.4). These data show two different structural styles within the Salton Sea: one south of the hinge faults offshore Bombay Beach and another along the eastern Salton Sea. Both components reveal details on young pull-apart basin formation and Southern California fault kinematics.

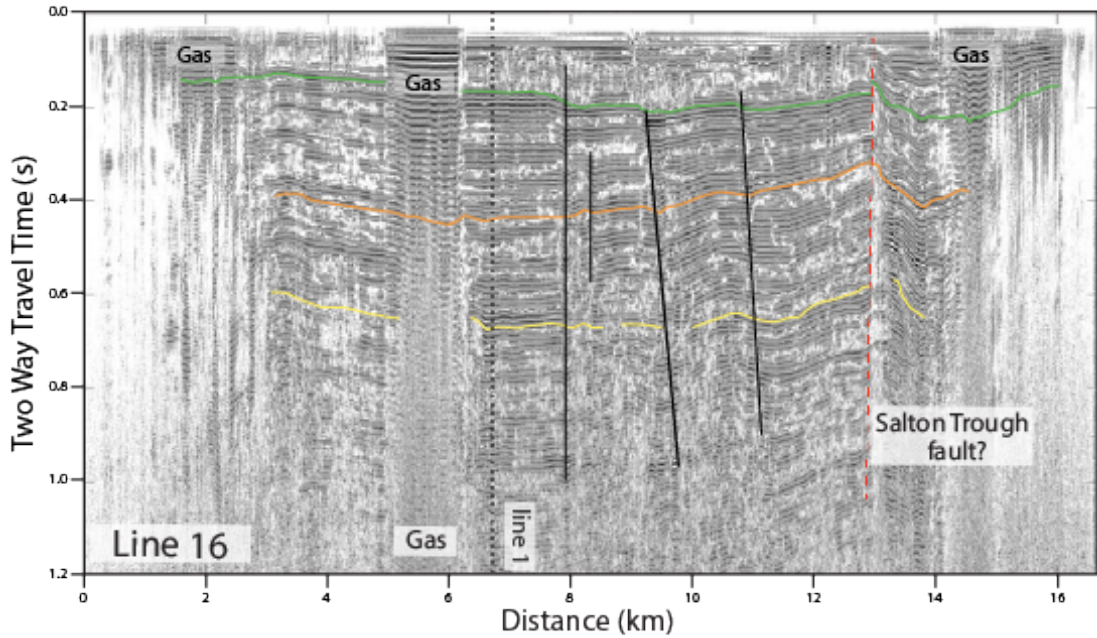


Figure 2.8: Line 16 2010. MCS Line 16 is located just south of Bombay Beach where the active SSAF enters the sea. The black lines are faults that display normal-slip displacements, while red dashed line highlights the location of the postulated Salton Trough fault, which has local compressional stratigraphic signature in this region. Note the vertical exaggeration makes the faults appear more vertical. Line 1 crossing is noted by black dots.

2.4 Discussion

Nested seismic profiles both parallel and perpendicular to the SSAF reveal distinct styles of deformation within the northern and southern sub-basins of the Salton Sea (Fig. 2.1). Line 1 (Figs. 2.3 & 2.4) images an active pull-apart basin in the southern sub-basin of the Salton Sea (SB in Fig. 2.1) and places direct constraints on the eastern bounding transform fault (Salton Trough fault, STF) that also reveals a long-term component of down-to-the-southwest extension. Evidence from the seismic data, both parallel and orthogonal to the SSAF, shows the transition from southwest-northeast oriented extensional deformation in the northern Salton Sea associated with the STF (Lines 19, 7 and 17) into the locus of extension characterized by southeast-northwest oriented extension ($\sim 90^\circ$ rotation in extension direction) within the pull-apart system (Fig. 2.1).

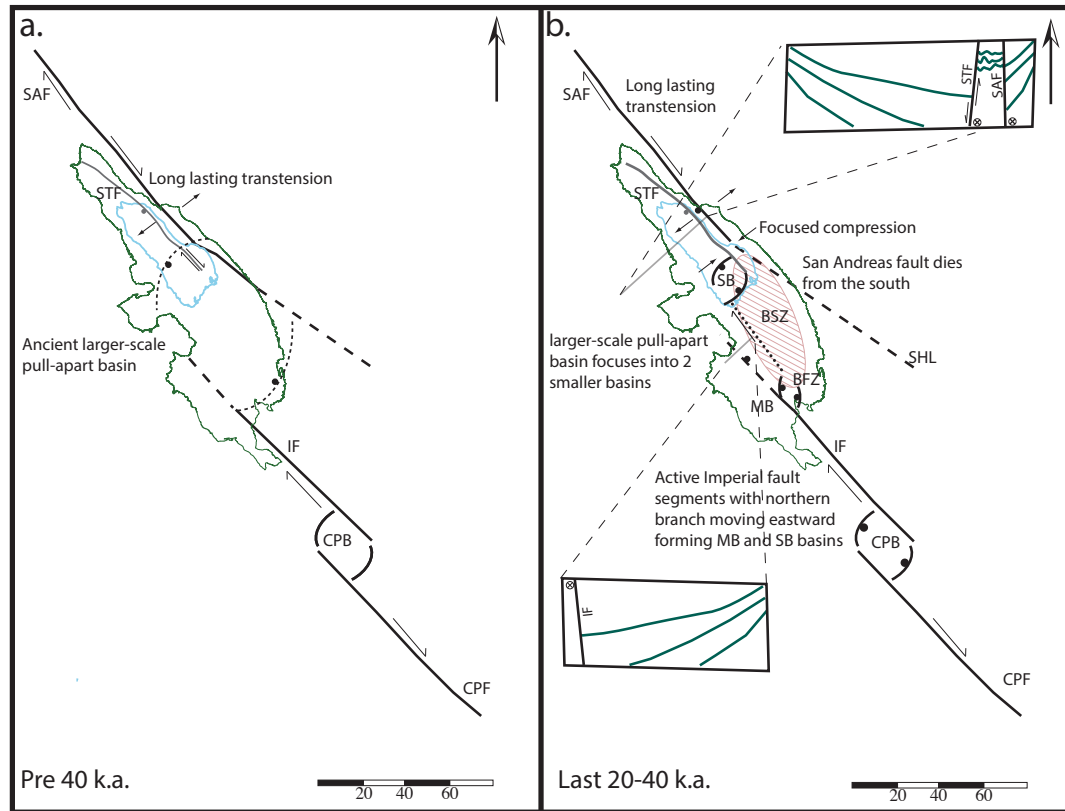


Figure 2.9: Salton Pull-apart Time Evolution. a, Before the formation of the Salton sub-basin pull-apart system, the active portion of the San Andreas fault possibly continued farther south, along the Sand Hills Lineament. (b) As the Imperial fault migrated northward, the most northerly section jumped northeastward forming the incipient Brawley fault zone, resulting in the abandonment of the Sand Hills section of the San Andreas fault. In this manner, the Mesquite and Salton sub-basins were formed. Evidence from Line 7 and 16 (and multibeam data) and the Mesquite Basin suggests that the Salton Trough fault and Imperial fault strike-slip systems may have a dip-slip component of motion being down toward the pull-apart basin (see insets).

The green horizon records the onset of focused extension within the southern Salton sub-basin, where a series of normal faults contribute to stratigraphic offset and accommodation (Figs. 2.3 & 2.4). The suite of faults in the hinge zone consistently exhibits a down to the southeast offset. This together with their orientation suggests they are not related to the mapped EFZ (left lateral faults) onshore (Hudnut *et al.*, 1989). The northeast-southwest trend of these faults is consistent

with predictions regarding pull-apart basin models (R faults of *Basile and Brun* (1999)). Assuming that the Holocene sedimentation rate of 1-2 cm/yr calculated by *Brothers et al.* (2009) is persistent, a remarkably short amount of time (~ 2040 k.y.) is recorded by the stratigraphic wedge observed within the NW-SE oriented reflection profiles (above the green horizon). Sedimentation rates published within the Salton Trough (e.g., *Meltzner et al.* (2006)) reveal lower rates between 4-8 mm/yr, but because our study is located within the current depocenter of the Salton Trough, the higher rates are employed for age estimates. Beneath this important stratigraphic horizon, sedimentary layers show a greater degree of concordance with evidence of local thinning in this region (observed when comparing mapped horizons in Figures 2.3 and 2.4). These observations are consistent with the predictions of a northwestward propagating pull-apart system. Specifically, this model predicts that the southern end of the SSAF migrates north through time, in concert with the formation and/or growth of the BFZ to essentially “lengthen” the greater IF system. Tectonic evidence suggests that the SSAF extended much farther south in the past (>100 km, Fig. 2.9a) encompassing the now abandoned segments of the Sand Hills fault (Fig. 2.1; *Lynch and Hudnut* (2008)), and possibly as far south as the Altar fault (*Pacheco et al.*, 2006). The diminishing slip on the southernmost section of the dying SSAF was likely accommodated by the northward growth and slip on the BFZ, with an attendant northward migration of extension.

The slight eastward jog of the BFZ (relative to the IF) provides the necessary geometry to engender focused extension within the Mesquite and Salton pull-apart sub-basins, and possibly explains the juvenile right step to transfer motion north-eastward and the youthful expression of the BSZ (e.g., skewed right step/ $\sim 350^\circ$ directed geometry with a diffuse seismicity pattern, Figure 2.1). Thus, a geographically larger, less focused, pull-apart basin spanning the Imperial-San Andreas system gives way to more focused extension within the Mesquite and southern Salton sub-basin bounded by a right lateral system initiating within the BSZ (Fig. 2.9).

Lines 17, 7 and 19 are located offshore the NE shore of the Salton Sea (Fig.

2.1) adjacent to the active (currently creeping) portion of the SSAF (*Lyons and Sandwell, 2003*). The sense of motion recorded in the northern sub-basin reflection profiles, down to the NE, with eastward-fanning dips, continues to a depth of 3+ km, implying a lifespan longer than 150-300 k.y. for the southern pull-apart basin based on sedimentation rates of 1-2 cm/yr (*Brothers et al., 2009*). If the northern sub-basin has lower sedimentation rates a significantly longer lifespan can be assumed. The thickening of strata toward the northeastern shore of the Salton Sea provides evidence for (a) a normal component of slip along this section of the SSAF, with a down-to-the-southwest fault geometry, (b) uplift of the Santa Rosa mountains causing the tilting of the strata observed along Lines 19, 7, and 17 (Figs. 2.5, 2.6, and 2.7). (c) Loading of a foreland basin (Salton Sea) by uplift along a NE-dipping SSAF. (d) Normal offset along an offshore parallel fault, some 1-2 km west of the SSAF in the vicinity of the sharp anticlinal axis identified on Line 16, or Option (a) is similar to sedimentation observed in many extensional environments (e.g., *Driscoll and Karner (1998)* and references therein). Option (c) is similar to geometry observed in foreland basins (*Bally, 1983*). Option (d) is very similar to that observed along the Cerro Prieto Fault, where the nearby parallel striking Mesa Fault partitions slip between normal motion to the west and strike-slip along the Cerro Prieto Fault (*Chanes-Martinez et al., 2014*).

We do not prefer option (a) because off-fault seismicity patterns, surface geology, and reflectivity along the SSAF suggest a NE-dipping SSAF with a small component of up-to-the-northeast dip slip (*Lin et al., 2007; Fuis et al., 2012; McNabb, 2013; Fuis et al., 2014*). Modeling of geodetic and InSAR data to the east of the Salton Sea (*Fialko, 2006; Lindsey and Fialko, 2013*) also strongly suggests a geometry consistent with the seismicity data (northeast dipping SSAF). Such a dip is also consistent with the geomorphology and onlapping of the alluvial fans east of the SSAF (Figure 1; *McNabb (2013)*). Option (b) is not consistent with the stratal geometry in the basin as uplift of the Santa Rosa Mountains would cause truncation along the western Salton Sea and onlap along the eastern shore (Fig. 2.10b) Option (c) is not a preferred explanation for the sediment divergence observed in the northern basin of the Salton Sea. A forearc system would have uplift

expressions along the length of the Salton Sea, not just in the Durmid Hill area. Additionally, forearc systems show maximum subsidence adjacent to the fault (Fig. 2.11,(c)). Within the Salton Trough, the maximum subsidence is within the Salton Sea, and the Borrego Fm. (adjacent to the SSAF) is uplifted. The uplifted Borrego Fm. between the eastern shoreline of the Salton Sea and the SSAF suggests an additional control on the tectonic deformation in the region.

We favor option (b; Fig. 2.11d), namely because the NE directed fanning is indicative of a SW dipping fault structure with maximum divergence adjacent to that structure. We also observe evidence that may suggest a fault plane in stratigraphic truncations along Line 7 (Fig. 2.6) and observations of a strong bathymetric scarp along the NE shoreline of the Salton Sea (Fig. 2.5, inset) in the vicinity of Line 19 that is colinear with the features observed on Lines 7 and 16 (Figs. 2.6 & 2.8). It is important to reiterate that Lines 19, 7, 17 and 16 (Figs. 2.5, 2.6, 2.7 & 2.8) exhibit both direct and indirect evidence in the Salton Sea for the presence of a parallel dextral strike slip fault (STF) near the shoreline of the Salton Sea, which is characterized by an extensional component along most of the imaged fault trace (Fig. 2.1). The hinge faults imaged by *Brothers et al.* (2009) consistently show a down to southeast offset (Figs. 2.3 & 2.4). The faults imaged on Line 16 between 8 – 12 km show an apparent down to the northeast component of slip (Fig. 2.8), which is consistent with the azimuth of Line 16 and the trend of the hinge faults (Fig. 2.1). In contrast, the STF imaged at ~13 km exhibits a very different deformation style being folded with minor offsets (Fig 2.8). Our preferred interpretation based on the seismic data is the easternmost fault on Line 16 is the SFT and the faults to the west are the hinge faults (R faults of *Basile and Brun* (1999)). There has been recent conjecture regarding the possibility of such a fault structure offshore within the Salton Sea (e.g., *Janecke* (2013)); the offshore stratal geometry presented here together with onshore mapping provide compelling evidence for the existence and location of this fault strand (Fig. 2.1).

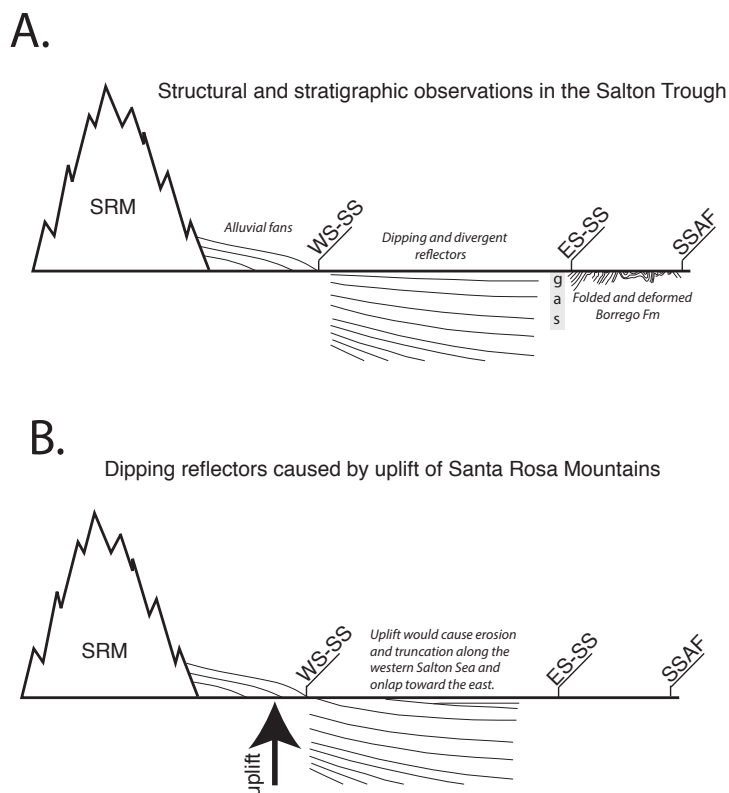


Figure 2.10: Schematic of structural and stratigraphic observations from the Salton Trough, Part I. (a) Folded and deformed sediments of the Borrego Fm are exposed east of the eastern shoreline of the Salton Sea (ES-SS) and alluvial fan deposits are observed along the western shoreline (WS-SS). Along the eastern shoreline the Borrego Formation dips toward the sea (Babcock, 1974). Note the dipping reflectors imaged in the sea; the dip systematically increasing down section (divergence). Gas wipeout of the acoustic signal is observed along the eastern margin. The location of the southern San Andreas Fault (SSAF) is shown. Cross section is coincident with Line 7 shown in Figure 2.5. (b) If uplift of Santa Rosa Mountains (SRM) caused the rotation and dip of the reflectors imaged within the sea, then there should be erosion and truncation along the western margin of the Salton Sea.

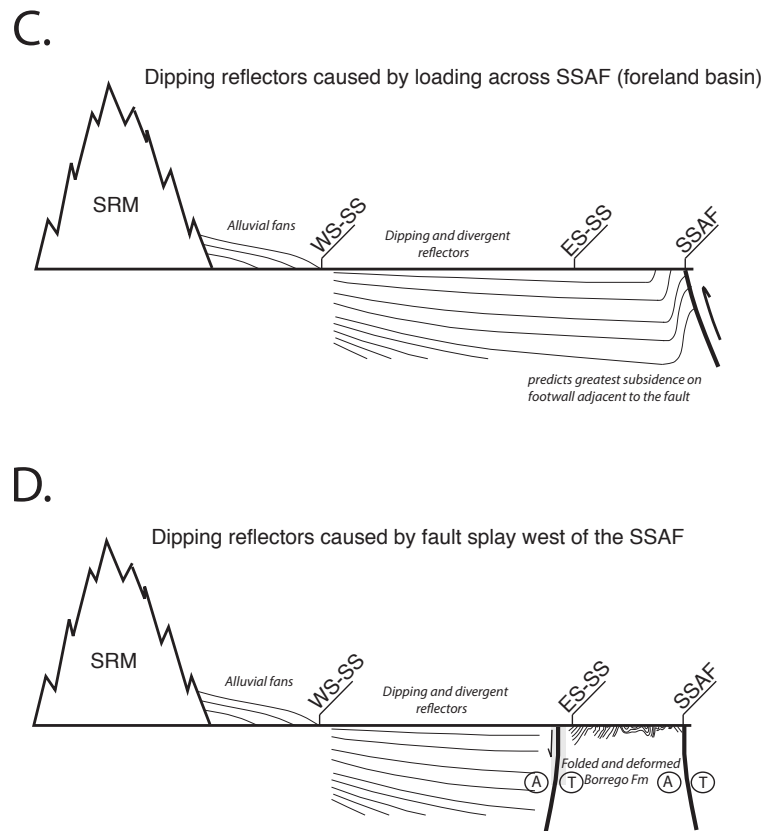


Figure 2.11: Schematic of structural and stratigraphic observations from the Salton Trough, Part II. (c) If shortening across an eastward dipping SSSAF with attendant loading of the footwall caused the dipping reflectors observed in the sea, then maximum subsidence should be adjacent to the fault. The predicted subsidence patterns are not observed as the thickest sediment in this scenario would be adjacent to the SSAF (d) Preferred explanation for dipping reflectors observed in the Salton Trough. A long-lived strike-slip fault splay west of the SSAF in the Salton Sea with down-to-the-southwest (dip-slip) deformation explains the stratigraphy in the sea as well as the uniform dip along the eastern shoreline of the Borrego FM. The location of the fault splay is also consistent with the location of the gas (fluid expulsion) as faults are often conduits for fluid flow. Fault scarps also are observed farther north in the swath bathymetry data (Fig. 2.5b)

Some have argued (*Dorsey et al.*, 2012) that the eastward-fanning dips observed in the Salton Sea cross Lines (19, 7, 17, 16; Figs. 2.5-2.8) are actually related to uplift and tilting of the nearby Santa Rosa mountain (SRM, Fig.2.1) range to the northwest, which would produce the observed northeast tilt of stratigraphic layers (Fig. 2.10b). The amount of uplift within the SRM is several times the depth of Lake Cahuilla (*Dorsey et al.*, 2012), implying that if the western side of the Salton Sea was being broadly uplifted, sediments would be eroded and reworked as they were raised above base-level defined by highstands of Lake Cahuilla. Thus, the SRM uplift would preferentially remove/erode sedimentary horizons toward the southwest, with preferential preservation and bed thickening near the eastern side of the Salton Sea. Erosional surfaces, angular unconformities, nor onlap are observed in the seismic reflection data along the southwest shore of the Salton Sea to support this alternative explanation (e.g., *Dorsey et al.* (2012)).

The preferred explanation for the divergence dips observed in Lines 17, 7 and 19 (Figures 2.5, 2.6 & 2.7) is option (d) above, with a long-term southwest component of dip-slip offset across the inferred fault along the eastern shore of the Salton Sea, STF (Fig. 2.11d). The observed stratigraphic growth is most consistent with the presence of an additional fault near the eastern shoreline of the Salton Sea where subsidence is maximum. The existence of the STF may help explain the inconsistency between seismicity (and other geophysical evidence mentioned above) observed adjacent to the SSAF and the need for a west-dipping structure to accommodate the sediment divergence.

Structural and stratigraphic predictions for the different mechanisms or hypotheses to explain the northeast dipping horizons observed in the seismic reflection data are shown in Figure 2.10 and 2.11. The schematic cross section is located near Line 7 from the SRM in the west across the Salton Sea to the SSAF in the east (Figure 2.1). In all scenarios, the SRM are highstanding features, resulting in an alluvial fan building toward the southwestern shoreline of the Salton Sea (WS-SS). Within the Salton Sea, Line 7 reveals divergent reflectors dipping (and thickening) toward the northeast, that are obscured by gas near the eastern Salton Sea shore (ES-SS). Between the ES-SS and the SSAF, stratigraphy of the

Borrego Formation has been deformed and folded (*Babcock*, 1974), with a persistent southwestward dip of these sediments near the shoreline (Fig. 2.10A) and interpreted by *Babcock* (1974) as the dip of a major structure. If the dominant structural control for stratigraphy within the Salton Sea were SRM uplift, there would be both truncation and onlap of stratigraphy within the Salton Sea (Fig. 2.10B). If the dominant structural control was an eastern dip on the SSAF (i.e., foreland basin model, option (c), Fig. 2.10C), then more broadly associated folding would be observed, with a signature that extends far to the southwest (Fig. 2.10C). The presence of a separate and distinct STF with a down to the southwestward component of slip (Fig. 2.10D) is more consistent with the offshore and onshore observations adjacent to the creeping portion of the SSAF. Line 16 (Fig. 2.8) does show evidence that the STF continues into the Salton sub-basin though the sub-basin is under compression along the NE-SW axis. For this reason, a signature of vertical offset is not observed.

New work by *Hammond et al.* (2014) shows a component of vertical deformation near this southern segment of the SSAF using geodetic arrays, providing additional evidence for the presence of down-to-the-southwest motion in the region that is consistent with other observations for the STF. The MCS data presented here do not have the resolution required for vertical slip rate estimations, and there is a dearth of deep cores in the Salton Sea that could be used for age constraints. Despite these limitations, *Hammond et al.* (2014) calculates 1 to 2 mm/yr of vertical subsidence along the southern SSAF system from Geodesy. MCS profiles 7, 19 and 17 (Figures 2.5, 2.6 and 2.7) show long-term accommodation (>100 k.y.) indicating a down to the southwest component of motion. Both direct and indirect evidence in the seismic data, along with a small offset scarp in bathymetric data (Fig. 2.5b), suggest the existence of a fault within the Salton Sea that strikes subparallel to the SSAF. *Tong et al.* (2013) combine InSAR data with geodetic measurements to reveal a section of subsidence north of the Salton Sea that may indicate a northwesterly extension of the STF beyond the lake coinciding with the northernmost extent of the Salton Trough (Fig. 2.1) that may extend up to 80 kilometers in length or more. This extension is contradicted by onshore reflection

data (*Fuis et al.*, 2014).

The presence of a significant fault parallel to the SSAF helps unify discrepancies between seismic data collected within the sea and modeled data adjacent to the SSAF. The STF fault likely serves as the eastern bound of the current pull-apart basin, aligning as the western boundary of the “rung-and-ladder” seismicity offshore Bombay Beach (Fig. 2.1). The presence of this parallel fault strand adjacent to the SSAF may help explain some observations in the paleoseismic record (*Philibosian et al.*, 2011), which highlights an extended record of non-rupture (in comparison to other periods between paleo-ruptures). Perhaps the STF plays an important role in strain release along with the SSAF, so a combined record of rupture history may be required to properly assess long periods of non-rupture on the SSAF and whether such a period is anomalous (e.g., would an early 19th century rupture on the STF lessen the concern regarding the current nature of non-rupture on the SSAF?).

Beyond these first order architectural observations within the sea, the hybrid pattern of deformation observed on and near Line 16 is perhaps not that unusual given its location is at intersection between the northeasterly trending normal faults in the pull-apart basin, and the bounding northwest trending dextral STF that also displays some down-to-the-southwest normal motion. This distinct region of compression/transpression gives insight into the inherent complications of pull-apart basins (Fig. 2.9).

The fault architecture in this region reveals a complicated view of the pull-apart progression and evolution in that the vertical motion in the northern sub-basin, outside of the Salton sub-basin proper (along the strike-slip faults, observed on profiles perpendicular to the STF) is longer lived than the focused activity in the southern sub-basin. This signal may be related to flipping between a mode of generally wide-spread transtension within the ImperialSan Andreas pull-apart system, to more focused deformation associated with the development of the BF and extension within the Salton and Mesquite sub-basins. Furthermore, the architecture of pull-apart bounding faults exhibits a down-toward-the-pull-apart-basin motion near their terminus (Figure 2.9).

2.5 Conclusions

Nested seismic reflection profiles, P wave tomographic images and multi-beam bathymetry place important constraints on the temporal and spatial evolution of deformation within the Imperial-San Andreas pull-apart system based on the stratal geometry imaged beneath the Salton Sea. The data reveal a strong difference between a mode of extension in the southern Salton Sea (Salton sub-basin) versus the northern Salton Sea (northern basin). Findings also provide strong evidence for a fault within the Salton Sea (the STF) that runs sub-parallel to the SSAF.

As strike-slip systems evolve, some fault strands may wane while others grow through propagation; this process has the potential to abandon the larger, more mature, regional pull-apart basin in favor of the formation of focused systems, such as the Salton and Mesquite sub-basins. Seismic profiles show the transfer of strain from the Imperial fault onto the SSAF, though the Salton Sea pull-apart basin. This translates into a zone of compression in the NE-SW directions (Fig. 2.8) and overall extension in the NW-SE directions (i.e., parallel to the SSAF, Figs. 2.3 & 2.4). Findings reveal that continued redistribution of slip between the Brawley fault and the STF (both dextral fault systems) formed the modern Mesquite and Salton pull-apart systems.

This study also reveals that the San Andreas fault is closely paralleled by the long-lived Salton Trough fault that is indirectly and directly observed with these new data. Indications are that the STF bounds the rung-and-latter seismicity offshore Bombay Beach, and continues onto land north of the Salton Sea. Based on the thick diverging packages, the STF is long lived and has contributed to the formation of the northern sub-basin though the implications of the STF from a seismic hazard standpoint are unknown.

The combination of multi-scale seismic reflection and seismic refraction provides insight to the evolving segment boundaries in southern California and the interplay of strain partitioning between these active fault zones. The inherent complications within this system (i.e., zones of transpression and transtension) may also play a part in the communication of stress during earthquake triggering

scenarios, either inhibiting or promoting dynamic or static triggering mechanisms (*Hudnut et al.*, 1989; *Brothers et al.*, 2011).

2.6 Acknowledgements

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Chapter 2 can be found in Kell, A. M., Sahakian, V.J., Kent, G. M., Driscoll, N. W., Harding, A. J., Baskin, R. L., Barth, M., Hole, J. A., Stock, J. M., and Fuis, G. S., “New Constraints on the Architecture and Evolution of the Imperial-San Andreas Pull-Apart System Beneath the Salton Sea, California”, *submitted to Geosphere*.

Chapter 3

Geophysical evidence for a San Andreas Fault splay in the Salton Sea

3.1 Introduction

The Southern San Andreas Fault (SSAF, Fig. 3.1) in Southern California is an important part of the Pacific-North American plate boundary system, accommodating 21 – 25 mm/yr of the boundary's total 50 mm/yr of slip (*Bennett et al.*, 1996; *Fay and Humphreys*, 2005; *Lundgren et al.*, 2009). At its southern terminus the SAF steps west over to the Imperial Fault (IF) creating the Salton pull-apart basin through a releasing bend in the right-lateral system (*Brothers et al.*, 2009). The basin architecture is complex, involving the interaction of many smaller faults including the Extra fault zone and Brawley Seismic zone (*Brothers et al.*, 2009; *Lynch and Hudnut*, 2008). The SSAF/IF system has the potential of generating a large magnitude earthquake (*Brothers et al.*, 2011), which would affect a large portion of the populated areas in Southern California (*Olsen et al.*, 2006). Paleoseismic data indicates that there has not been a rupture on the southern (Coachella) SSAF in the last 300 years (*Brothers et al.*, 2011; *Philibosian et al.*, 2011). During historical times, there have been at least 2 events (1940 & 1976) on

the IF, neither of which triggered slip on the SSAF (*Hartzell and Heaton, 1983; Thomas and Rockwell, 1996*). *Brothers et al.* (2011) proposed yet another potential triggering mechanism unrelated to tectonic loading. They suggested that loading the Salton Sea with water from the captured Colorado River could trigger normal faults present in the Salton Sea (*Brothers et al., 2009*) thereby increasing the Coulomb stress on the SSAF and IF. Constraining the fault structure and potential fault interactions is the critical first step towards evaluating these triggering mechanisms.

The Salton Trough is located in Colorado deltaic system in southern California (*Waters, 1983*). Prehistoric flooding of the Colorado River into the ancient Lake Cahuilla yielded high sedimentation rates in the recent geologic past, and these sediments record past and present tectonic signals in their deformational style (*Waters, 1983*). Active source seismic data (both reflection and refraction, track lines shown in Fig. 3.1) provide important constraints on fault architecture by imaging the deformation of the sediments and the style of faulting within and adjacent to the Salton Sea. Previous studies using earthquake locations and geodetic data (*Fialko, 2006*) model a slight northeastern dip on the SAF. Imaging stratigraphy adjacent to the SAF provides direct spatial and temporal observations reflecting current and historic fault displacement and timing, as well as the style of faulting and the local tectonic regime.

Data presented in this study provide evidence for a splay west of the SSAF located within the Salton Sea near the eastern shoreline. This newly identified structure is referred to as the Salton Trough Fault (STF). This structure, though not directly imaged, is presumed to be a slightly southwestward dipping transtensional, right-lateral strike slip fault with down-to-the-southwest geometry. The existence of the STF has implications for rupture scenarios in the Salton pull-apart basin, via the linkage of fault segments through dynamic and static stress triggering (i.e., the SAF, IF, and SJF). Such an understanding will improve our ability to assess regional geohazards.

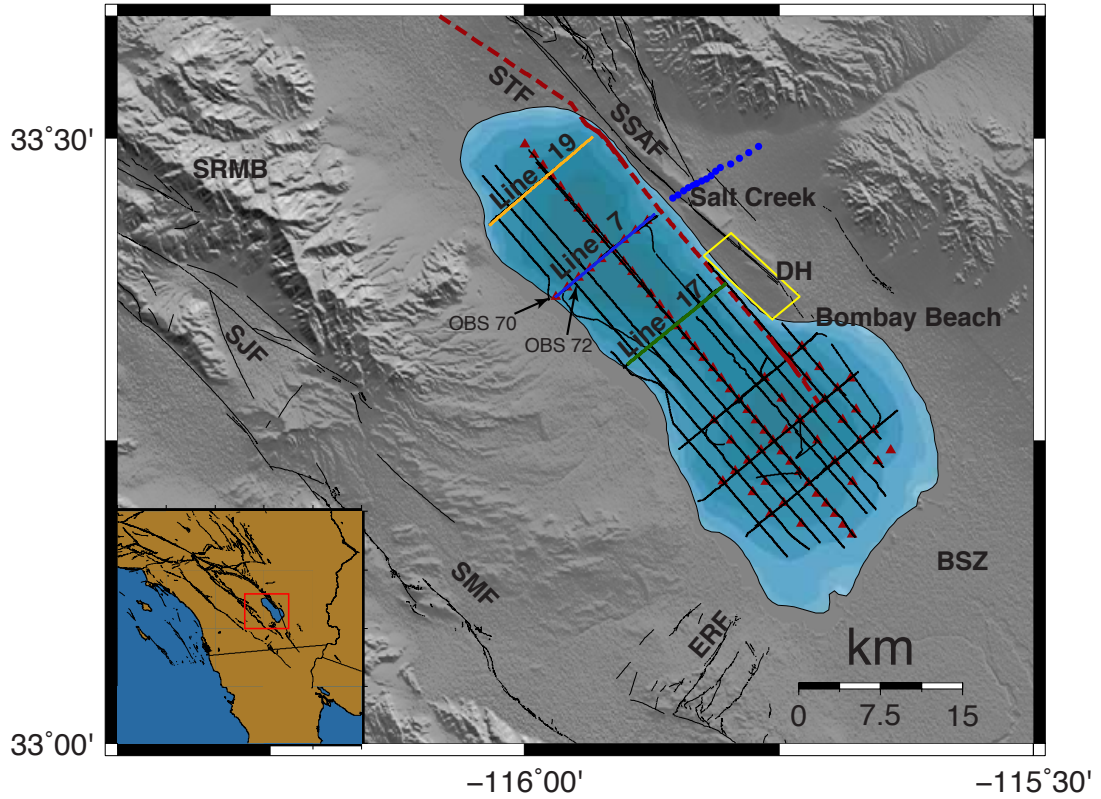


Figure 3.1: Region of Study. Inset: Regional map of southwest United States and Mexico. The red rectangle indicates the region of study. Main Map: Region of study – red triangles denote OBS locations, and blue circles denote land shots used in the velocity model for Line 7. The yellow box shows the location of Fig. 10. Thin black lines in the sea denote all MCS lines collected during the experiment. Green Line - MCS Line 17; Purple line - MCS Line 19; Light blue line - MCS Line 7; Fine black lines are USGS faults. Red line shows the location of the newly identified Salton Trough Fault (STF). SSAF - Southern San Andreas Fault; SJF - San Jacinto Fault; SRMB - Santa Rosa Mountain Block; ERF - Elmore Ranch Fault; BSZ - Brawley Seismic Zone; DH - Durmid Hill; SMF - Superstition Mountain Fault.

3.2 Methods

An active-source seismic study was performed within the Salton Sea and acquired Multi-Channel Seismic (MCS) reflection profiling with refraction data recorded by Ocean Bottom Seismometers (OBS). The overarching goal was to define the displacement, dip, and timing of deformation on the SSAF, as well as the evolution of the Salton pull-apart basin (*Kell, 2014*). The newly acquired

data, together with existing microseismicity and geodetic, data provide a more comprehensive understanding of fault architecture. This survey was performed in 2010 and 2011 as two marine campaigns in conjunction with the Salton Seismic Imaging Project (SSIP, (*Rose et al.*, 2013)). The SSIP used land based receivers and source locations in combination with offshore source/ receiver pairs to image the overall structure within the Salton Trough. The two portions of the marine campaign provided differing resolutions in the seismic profiles; 2010 implemented a smaller sparker source aimed to image the shallower sediment and in 2011 a larger air gun source was utilized to resolve deeper sediments. In 2010, MCS data were collected with a 1.6kJ sparker source fired at 3.34 meter (1.2 second) intervals and a 24-channel streamer with 3.125m hydrophone group spacing. A 210 cu. in. GI gun source was employed in 2011, with a shot spacing of approximately 35.5 meters (1 minute intervals). These shots were recorded by a 48-channel streamer with 12.5m group spacing for MCS data, as well as by OBS instruments deployed on the seafloor by Scripps Institution of Oceanography OBS Lab. Some of the SSIP land-sourced shots to the east of the SSAF were recorded on the 9 OBS instruments along Line 7 and included in a tomographic inversion to constrain velocities across the SSAF (Fig. 3.1). The land shots used explosives between weights of 3 and 162 kg and were spaced at an average of 105 meters, and were buried between 2.4 and 21.9 meters depth. The distance between the last marine shot and first land shot was approximately 6 km (Fig. 3.1).

Aerial LiDAR data collected in November 2010 were used to constrain the onshore deformation (Fig. 3.1) and to confirm geologic mapping results from (*Babcock*, 1974). The LiDAR data also directed field campaigns in the region. It was collected in a five kilometer swath surrounding the Salton Sea, with vertical accuracy of approximately 9.25 cm and an average point cloud density of 5.1 points per square meter.

Processing of the MCS reflection data included filtering, predictive deconvolution, and common-midpoint stacking (i.e., Fig. 3.2). Travel-time picks from the OBS gathers were inverted using the method of *Van Avendonk et al.* (2004). This method iteratively reduces the travel time residuals through a series of lin-

earized inversions until a model with a suitable misfit (χ^2) is attained. For each linearized inversion, the method minimizes a cost function that is a combination of travel-time residuals, smoothing parameters (second derivatives), and model perturbation, adjusting the trade-off between fitting and smoothing until an intermediate target misfit, compatible with linearization assumption, is obtained. The weighted misfit functional value, χ^2 is characterized by:

$$\chi^2 = \frac{1}{N} \sum_{i=1}^N \frac{(T_{obs,i} - T_{pred,i})^2}{\sigma_{unc,i}} \quad (3.1)$$

whereby N is the total number of picks, $T_{obs,i}$ and $T_{pred,i}$ are the observed and predicted pick times, respectively, and $\sigma_{unc,i}$ is the assigned pick uncertainty. In this way, χ^2 is a descriptor of how well the model fits the data within the prescribed pick uncertainties. For the models presented here, the first arrival picks were assigned an uncertainty of 12 ms, the reflection picks 30 ms, and second arrival picks were assigned an uncertainty of 32 ms.

The first velocity model constructed for Line 7 (location shown in Fig. 3.1) was generated using a homogenous 1D layered starting model, and employed only first arrival picks. Subsequent velocity models included an interface generated by a priori constraints of the depth of a strong reflector in the MCS data (the yellow dashed line in Fig. 3.2b), and included second arrival picks (Fig. 3.3a). Velocity models also included arrivals from the high amplitude reflector that were observed in the OBS shot gathers and correlated with the two-way travel time (TWTT) of the strong reflector in the MCS data at the location of each OBS. Examples of picks from OBS 70 and 72 (near the western edge of Line 7, Fig. 3.1) are presented in Fig. 3.3. The interface represents a transition in material properties, and as such, a velocity jump is assigned across the interface. Picks are assigned as either rays turning in the first layer above the interface, rays turning in the second layer below the interface, or rays reflecting off the interface. In Figs. 3.3a and 3.3b, black lines denote rays turning in the first layer, pink are rays turning in the second layer, and blue are reflections. The inversion simultaneously minimizes the travel-time residuals for all three of these types of picks as well as TWTT picks of the MCS reflector, and updates the model according to the new velocities of

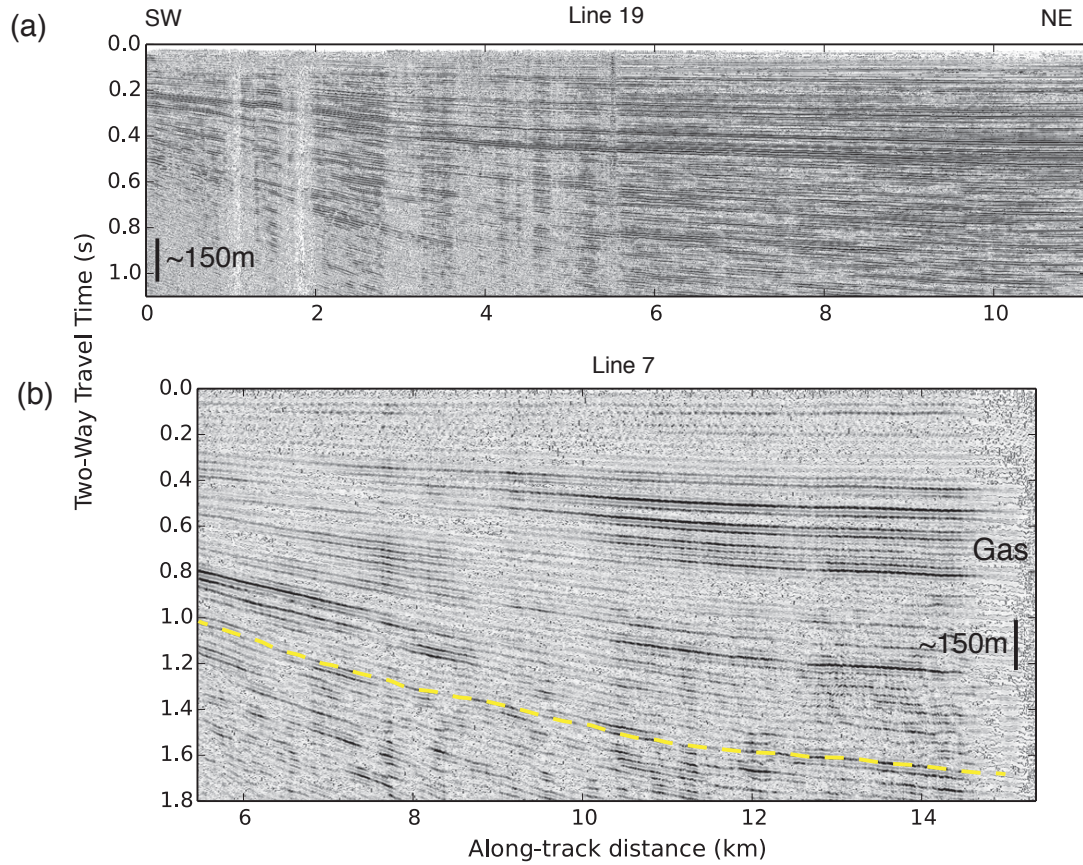


Figure 3.2: MCS Lines 19 and 7. (a) Line 19 (2010 sparker MCS data) is the northernmost line. Layers thicken and dip to the east, with no fault offset imaged within the profile. Some gas is observed and creates vertical acoustic striping. (b) Line 7 (2011 GI-gun MCS data) is offshore of Salt Creek. Layers thicken and dip to the east, with the dip increasing with depth (i.e., divergent). The trend is persistent to the bottom of the profile, a depth of 1.8 seconds two-way travel time. The dashed yellow line denotes the high-amplitude reflection observed, which constrains the interface in the velocity model. Location of profiles is shown in Figure 3.1.

each layer, as well as the depth of the interface and velocity contrast across it. Note that for OBS 70 (Fig. 3.3a) there are both first and second arrivals that turn within layer 1; the reflection cannot be discerned for this instrument, though if it were, the second-arrival would be associated with its pre-critical reflection. OBS 72 is located at approximately 7 km along-track distance; the reflections arrival time at this distance also corresponds to the arrival time of the high amplitude

reflector at ~ 7 km distance on MCS Line 7 (Fig. 3.2b). The main difference in the velocity models is the location where the interface intersects the surface near the SSAF surface trace.

Occasionally the inversion stalls in local minima creating artifacts in the model that are not required to explain the data nor are consistent with a realistic earth structure. The nullspace shuttles method of *Deal and Nolet (1996)* was employed between some inversion iterations to reduce these artifacts. In these models, the sedimentary section above the interface was smoothed to obtain a more homogenous velocity model; this smoothed model was projected onto the model nullspace. The result is a model that is consistent with the data and improves the model fit in further inversion iterations. An example of this can be seen in Figure 3.4. Figure 3.4a shows a model before applying the nullspace shuttles method, and Figure 4b shows the smoothed model after the method. The black ellipses indicate regions where the nullspace shuttles method effectively smoothed out artifacts, improving the fit to the sedimentary basin. In this example, before applying the nullspace shuttles method, the models misfit stalled at $\chi^2 = 1.7$ and after applying the method and iterating further the model the misfit improves to $\chi^2 = 1.3$.

3.3 Results

3.3.1 Reflection Data

This paper focuses on seismic lines orientated perpendicular to the SSAF collected in the mid- to northern Salton Sea along the western side of the SSAF (Fig. 3.1). Acquired with the sparker source, Line 19, located ~ 7.5 km north of Salt Creek imaged layers thickening and dipping to the east (Fig. 3.2a). These layers diverge with increasing dip with depth; this stratigraphic trend is persistent down to about 1.0 second TWTT. No fault offset structures are observed along Line 19. To the south, Line 7 (Fig. 3.2b) is located approximately adjacent to Salt Creek and images similar stratigraphic architecture as observed on Line 19 (Fig. 3.2a); the stratigraphic layers thicken and dip to the east. Line 7 was acquired with a 210 cu. in. GI-gun in 2011 and yielded deeper penetration because of the

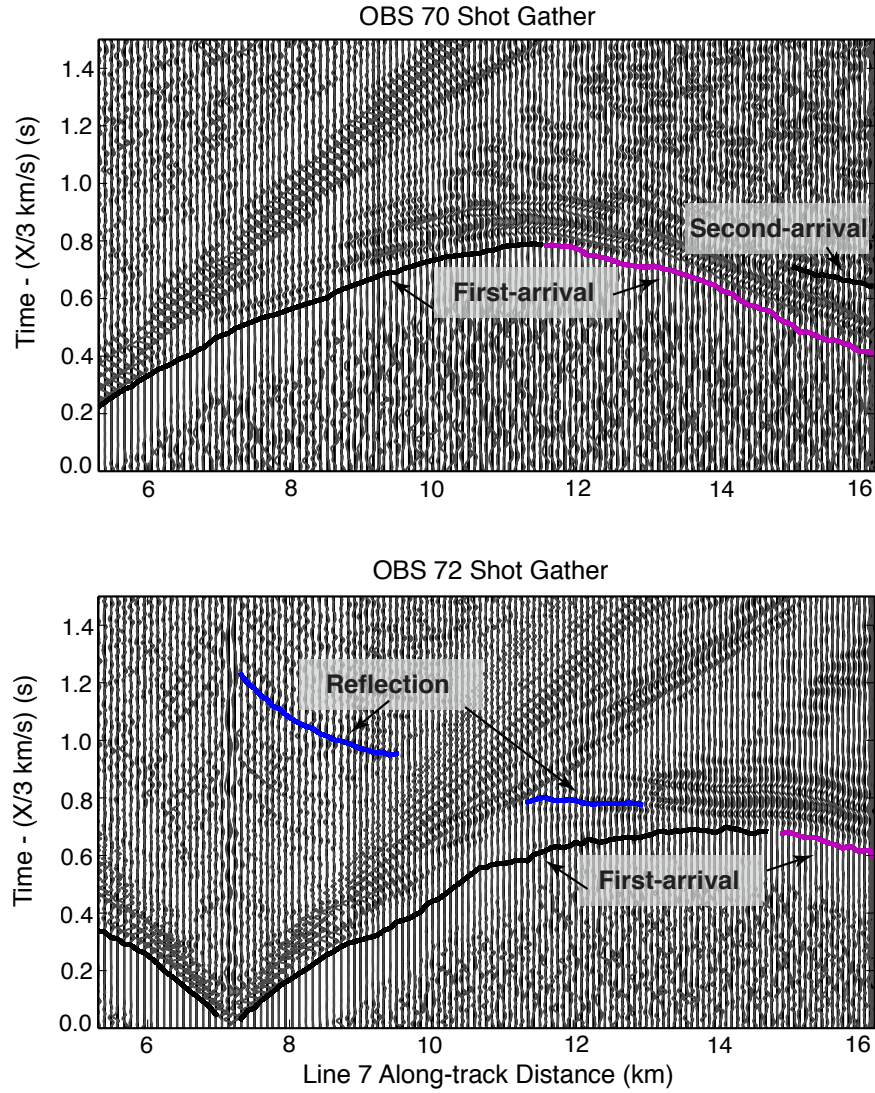


Figure 3.3: Two OBS shot gathers. (a) Shot gather of OBS 70 data for shots on Line 7. OBS 70 is located at approximately 4.5 km along-track distance on Line 7. First arrivals picks are shown by lines (Black - picks for rays that turn within the first layer; Pink picks for rays that turn within the second layer, below the interface) as well as second arrival (black, noted on profile). (b) Shot Gather of OBS 72 data for shots on Line 7. OBS 72 is located at approximately 7.1 km along-track distance. Travel-time picks are shown with lines. Blue picks: reflections associated with the triplication. Both shot gathers are plotted with a reduction velocity of 3 km/s.

lower frequency and larger sound source. This profile shows a divergent trend to at least 1.8 seconds TWTT (~ 2 km). In summary, the numerous high amplitude

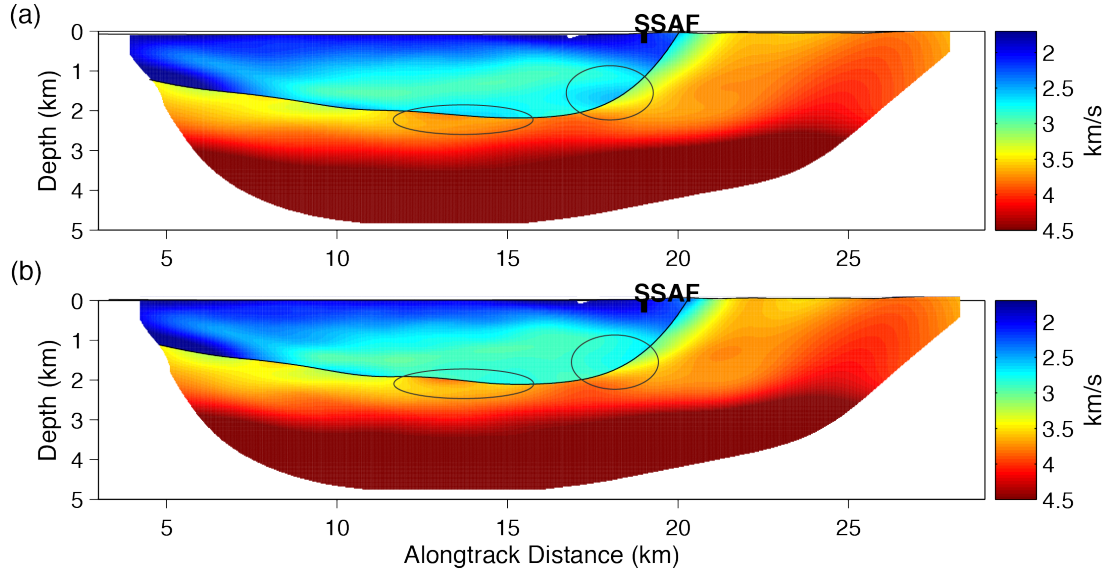


Figure 3.4: Shuttle comparison. (a) A velocity model for Line 7 before applying the null space shuttles method. (b) Line 7 velocity model after applying the nullspace shuttles method and iterating further upon the model. Black circles in (a) and (b) denote artifacts within the lake sediments that were reduced using this method.

reflectors on lines 19 and 7 are divergent (i.e., dip increases with depth) along the northeast region of the Salton Sea with no observed offset or faulting in the profiles (Fig. 3.2).

Continuing farther south, Line 17 (Fig. 3.5) crosses the Salton Sea slightly north of Durmid Hill (Fig. 3.1). Along both margins of the sea, the stratigraphy is obscured by gas. Within the central segment, stratigraphy is imaged down to depths greater than 1 second TWTT (~ 1 km). Unlike the profiles to the north (e.g., lines 7 & 19), Line 17 images a fault structure at approximately 6.5 km along track that separates predominantly flat-lying stratigraphy to the east from dipping horizons to the west (Fig. 3.5). West of the fault the dip of the reflectors increases downsection. Continuous undisturbed reflectors mantle the offset horizons across the fault with thicknesses on the order of 100 m. Another potential fault is observed at 4 km along track, but it is obscured by gas. Toward the northeast at ~ 10 km along track, Line 17 might cross the STF. The surficial stratigraphy east of the inferred fault has a slight southwest dip toward the structure. In this region, much

of the stratigraphic architecture is obscured by gas, increasing uncertainty and lowering our confidence of identifying fault offsets. The presence of gas also is consistent with the existence of a fault as it would be a potential permeability pathway for fluids. Farther south, on Line 16 (*Kell, 2014*), strata perpendicular to the SSAF strike are marked by extension interrupted by some transpressional faulting.

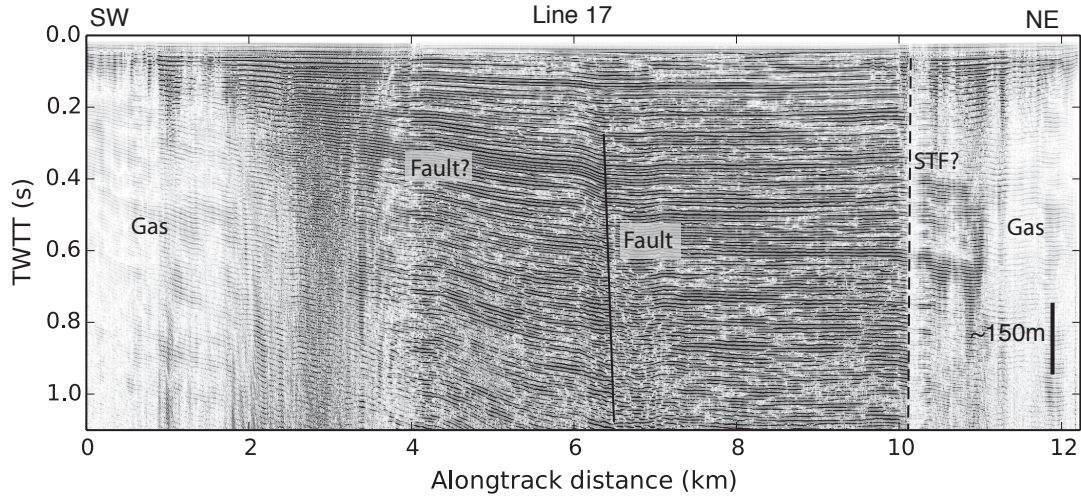


Figure 3.5: 2010 sparker MCS data, Line 17 is offshore Durmid Hill. Layers thicken and dip to the east. Fault marks deformation in strata from an inactive fault. Gas is present on the southwestern and northeastern edges of the line. To the northeast, surficial reflectors appear to dip and thicken to the northwest towards a potential fault structure (STF?). Location is shown in Figure 3.1.

3.3.2 Refraction Data

The initial, homogenous velocity model, as well as subsequent models, can be seen in Figure 3.6. Figure 3.6a shows topography along Line 7 from the Shuttle Radar Topography Mission sampled at 1 arc-second (SRTM1) (*Farr et al., 2007*) and bathymetric data. Figures 3.6b-f show the various velocity models for Line 7, plotted with a mask of one kilometer of confidence of the raypaths. The initial velocity model for Line 7 (Fig. 3.6b) shows an apparent southwestward dip to the velocities, with an increase to the northeast.. Approximately 1 kilometer northeast

of the SSAF surface trace, there is a southwestward-dipping high-velocity trend with surface expression. Along the surface the velocity systematically increases toward the northeast for a distance of ~ 7 km. Velocities range from approximately 2 km/s in the shallow lake sediments to approximately 4.5 km/s at about 4 km depth. The final misfit is $\chi^2 = 1.4$ is low but the model is only fitting first arrivals and includes few a priori constraints. At approximately 19-20 km along-track, there is a transition between two slopes or trends in the travel-time picks that is not well-resolved in the initial model.

Travel time residuals, travel-time picks and the Line 7 velocity model overlain with raypaths show pick density (Fig. 3.7a-c respectively). Hatch marks in Fig. 3.7b show the observed picks, and the lines are the predicted picks. Travel time trends transition from lower to higher velocities at $\sim 19 - 20$ km along track (Fig. Travel time residuals, travel-time picks and the Line 7 velocity model overlain with raypaths show pick density (Fig.3.7a-c respectively). Hatch marks in Fig. 3.7b show the observed picks, and the lines are the predicted picks. Travel time trends transition from lower to higher velocities at $\sim 19 - 20$ km along track (Fig. 3.6). There is a clear slower (< 2.5 km/s) trend to the southwestern edge of the profile, with faster velocities (> 3.5 km/s) to the northeast. Additionally, the OBS gathers record a distinct high-amplitude triplication suggesting a stronger velocity gradient than captured by the initial model (Fig. 3.6b). The vertical incidence time of the associated pre-critical reflection for each OBS match an along-track arrival of the high amplitude reflector observed in the 2011 MCS data.). There is a clear slower (< 2.5 km/s) trend to the southwestern edge of the profile, with faster velocities (> 3.5 km/s) to the northeast. Additionally, the OBS gathers record a distinct high-amplitude triplication suggesting a stronger velocity gradient than captured by the initial model (Fig. 3.6b). The vertical incidence time of the associated pre-critical reflection for each OBS match an along-track arrival of the high amplitude reflector observed in the 2011 MCS data.

Subsequent velocity models included a defined interface in an attempt to parameterize this gradient. Models test whether an eastward dipping interface, as observed in the MCS data (Fig. 3.2b, yellow dashed line), is consistent with

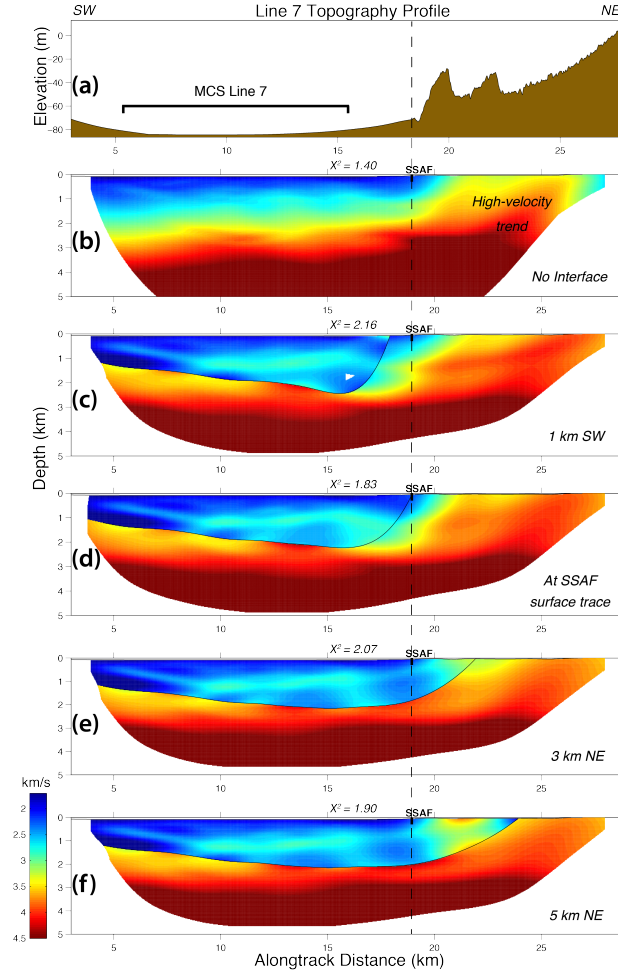


Figure 3.6: Line 7 refraction results. (a) Topographic profile of Line 7 from SRTM1 and bathymetry data. The bar shows the location of MCS Line 7. (b) (f) Velocity models with interface. SSAF surface trace of the SSAF. The dashed line shows the location of the SSAF on all the lines as well as on topography. The surface expression of the interface with respect to the SSAF is labeled on the bottom right of each panel. The misfit for each model is labeled top center. Colorbar for all model is on the bottom left. All models are masked to a 1 km extension beyond the ray coverage. (b) Initial Line 7 velocity model without interface. The high-velocity trend is marked here, and is present in the same region on the other models. (c) Model C with interface, the black line shows the location of the reflection interface, surfacing 1km southwest of the SSAF surface trace. (d) Model D, with interface intersecting at the SSAF surface trace. (e) Model E, interface intersecting at 3 km northeast of the SSAF surface trace. (f) Model F, interface surfacing at 5 km northeast of the SSAF surface trace.

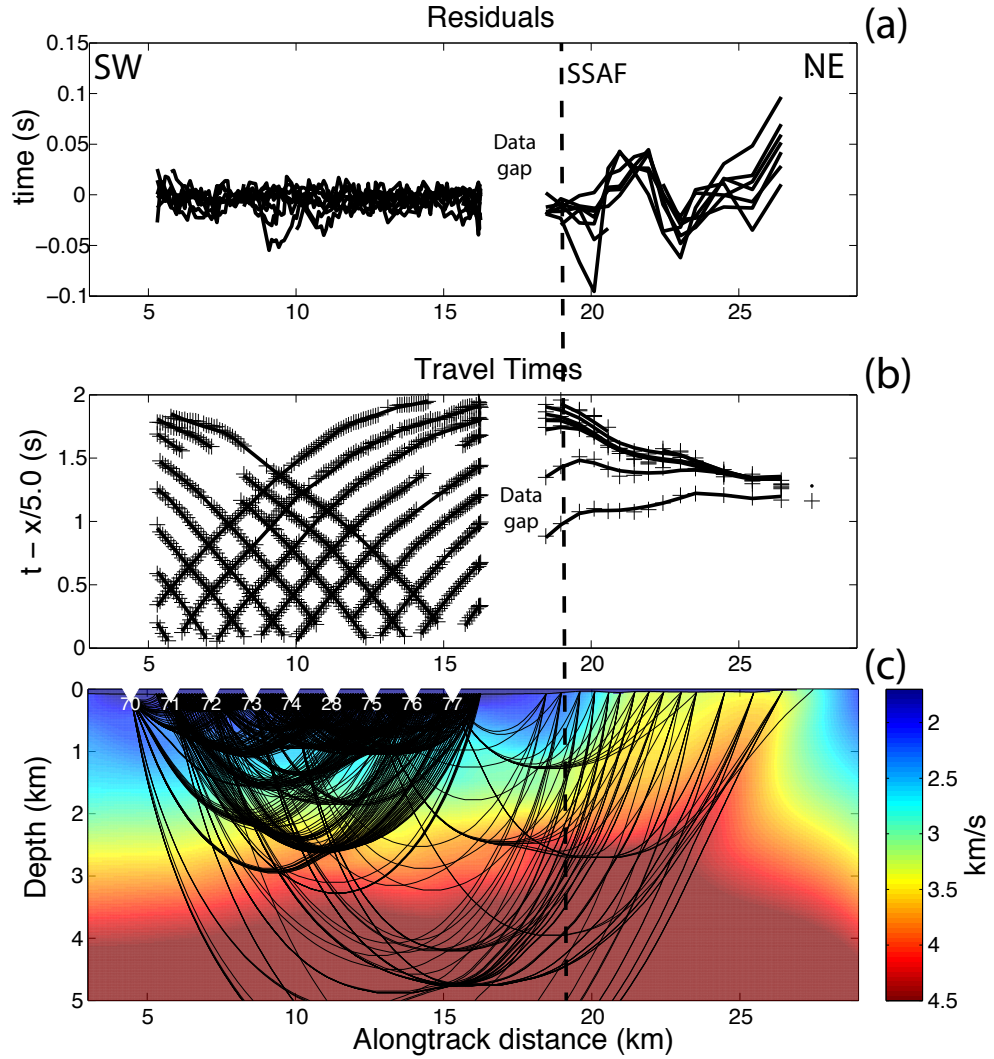


Figure 3.7: Initial model without the interface. There is a spatial gap in raypath coverage between 16 and 18 km due to no source or receiver coverage in the MCS or land shots near the shoreline. This is marked in (a) and (b). (a) Travel-time residuals. (b) Travel-time picks plotted with a reduction velocity of 5 km/s. Hatches are the observations, and the solid lines show the predicted picks. (c) Initial velocity model with raypaths plotted. OBS locations are plotted by white triangles.

the OBS data. When the refraction line was co-linear with existing MCS data, the depth of the interface was determined by converting the TWTT of the high-amplitude reflector to depth using the velocity model (Fig. 3.6b). Toward the northeast where MCS data did not exist, the location of the interface was guided

by the 3.2 km/s velocity contour up to the surface at a particular along-track distance. Three types of picks were assigned to constrain the model (described above in Methods), as well as TWTT picks from the MCS data for the reflector. This investigation resulted in 6 velocity models with varying locations for the intersection of the interface with the surface (black line in Figs. 3.6c-f). The velocity models and their respective misfits are plotted within a 1 km range of confidence around the raypaths. Figures 3.6c – 3.6f show the location of the interface moving toward the northeast. For example, Figure 3.6b is 1 km southwest of the SSAF surface trace and Figure 3.6f is 5 km toward the northeast of the SSAF surface trace. The model shown in 3.6d, the interface intersects the surface of the SSAF. From here on, these models will be referred to as models C, D, E, and F, to be consistent with their figure titles. All models show similar basement velocities below the interface to the southwest of the SSAF surface trace (~ 4.5 km/s). The main difference is in basin velocities southwest of the SSAF surface trace. The most pronounced velocity differences being observed in the northeastern portion of the model.

Models C through F feature slower velocities (< 3 km/s) in the basin that are similar to the sedimentary velocities in the initial starting model. The northeastern edge of the model contains higher velocities even in the shallow structures that have a western dip (Fig. 3.6). In Models C and D, the region around the SSAF surface trace, and just northeast the interface surface expression contains lower velocities in the range of 1.7 to 3 km/s as opposed to approximately 4 km/s as observed in the high velocity region. Models C and D have misfits of $\chi^2 = 1.40$ and 2.16, respectively.

Models E and F contain an interface that intersects the surface at 3 km and 5 km northeast of the SSAF surface trace, respectively. These models do display some higher velocity features within the basin east of the SSAF surface trace. The zones are interpreted as artifacts, though the nullspace shuttles method did have difficulty in completely smoothing the basin velocities, so this feature may perhaps be in part necessary to explain the data. The most interesting feature of these models is the high velocity package to the northeast of the SSAF. Both

models converge to lower velocities in region surrounding the SSAF surface trace, and progressively higher velocities moving northeast. They both demonstrate the need for a low velocity zone adjacent to the SSAF, skewed to the southwest. The respective misfits of these models are $\chi^2 = 2.07$ and 1.90.

Models with the interface intersecting the surface at 3 km to the southwest of the SSAF, and 1km to the northeast are not shown in Figure 3.6. The model with an interface at 3 km to the southwest forced the interface to have a very steeply dipping face; this created problems in convergence after only a few model iterations and as such has been omitted. The model with the interface intersecting the surface at 1 km to the northeast of the SSAF surface trace was not included because it does not differ significantly from models E and F.

Model F is the preferred or final model, because it simultaneously fits the two trends observed in the travel-time picks while converging to the lowest misfit. Constraints and raypaths for the final velocity model are shown in Figure 3.8. Figure 3.8a shows the travel-time picks for first and second arrivals as well as interface reflection arrivals. Raypaths are color-coded and the same for all panels. Travel-time residuals for all picks are plotted along-track, as well as the final velocity model with raypaths and OBS positions (Fig. 3.8a & 3.8c). Note ray coverage is significantly denser within the Salton Sea than onshore to the northeast (Fig. 3.8).

All models exhibit southwestward-dipping higher velocities on the eastern edge of the profile down to almost 3 km depth (Fig. 3.6). The preferred velocity model contains a dipping interface. In the southwestern part of the profile, the interface and shallow basin velocities mostly dip to the northeast, and in the eastern part of the model, they dip steeply to the southwest.

Figure 3.9 shows an overlay of MCS 2011 Line 7 data with the final refraction velocity model. The green line marks the high amplitude reflector highlighted in Figure 3.2b. The location of the interface is not fixed, rather it varies as a function of a tradeoff parameter between interface location, and velocity smoothness in the layers. It is important to notice that although the interface in the velocity model has been allowed to move in the inversion to fit all picks in the data, its depth is still within approximately 0.2 seconds of the high amplitude reflector in

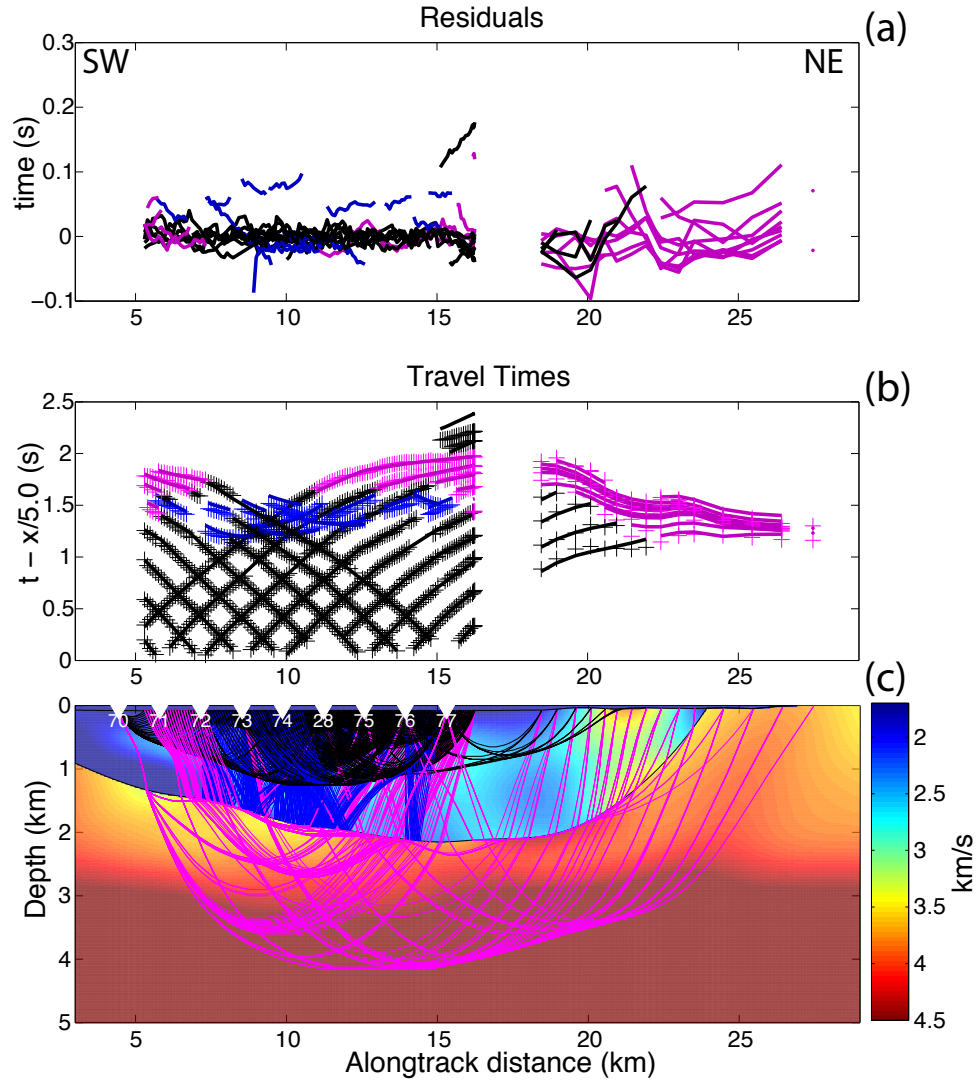


Figure 3.8: Preferred Model F. (a) Travel-time residuals. Pink rays turning within the second layer below the interface; Black rays turning within the first layer, above the interface; Blue reflections off the interface. (b) Travel-time picks plotted with a reduction velocity of 5 km/s. Hatches are observed picks, solid lines (following the color scheme of 8a) are the predicted picks for the final velocity model. (c) Raypaths in the final model. The color descriptions are the same as in 8a and b. White triangles denote OBS.

the MCS data.

Onshore geologic observations provide additional constraints on the STF. The Aerial LiDAR (Fig. 3.10) imagery show intense folding, shortening, and truncation of folds closer to the SSAF in the Durmid Hill region (approximately on-

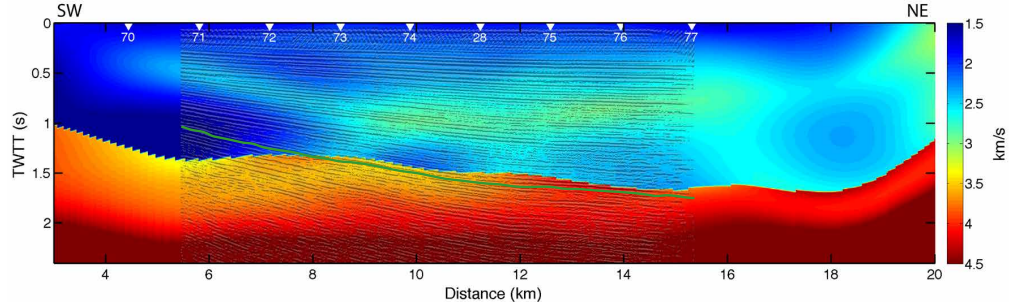


Figure 3.9: MCS 2011 Line 7 overlain with the final velocity model. The green line denotes the high amplitude reflector used to initially constrain the interface in the velocity model. White triangles show the OBS locations.

shore of Line 17). The strike and dip of the beds is highly variable. Both right and left-lateral offsets are observed in some of these layers. Moving southwest of the SSAF zone towards the Salton Sea shoreline, the wavelength of the folding becomes longer and more gentle, and the beds exhibit a much more consistent strike being subparallel to the shoreline. The dip decreases slightly towards the shoreline. White hatches denote positions of field measurements and photographs, and the red circle and arrow represent the location and approximate look direction of the photos in Figure 3.11. The beds imaged in Figure 3.11 have a strike and dip of N66°W and 57°SW respectively. The onshore strata adjacent to the shoreline have a persistent southwestward dip.

3.4 Discussion

It is assumed that the reflector (Fig. 3.2b) observed in the MCS data and shot gathers has a high amplitude because of a marked impedance contrast (i.e. a physical change in stratigraphic material). The reflector TWTT observed in the seismic reflection profile (yellow dashed line Fig. 3.2b) correlates with the zero offset arrival of the pre-critical reflection on each OBS instrument (Fig. 3.3). The character of this reflector suggests it is not the sediment basement interface, but could be related to a difference between surficial lake sediments and more indurated and compacted sediments beneath. It also could be a metamorphic contact due to emplacement of volcanic sills at depth, with thermal alteration and metamorphism

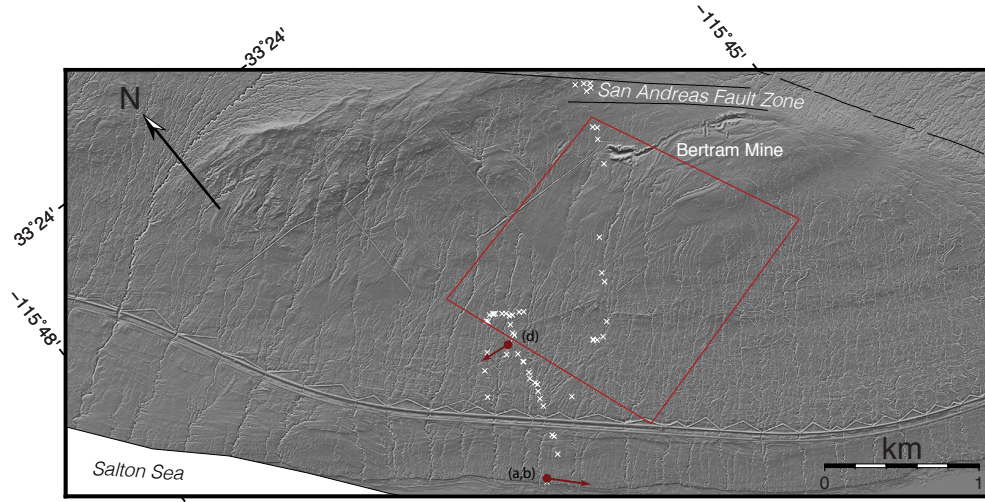


Figure 3.10: Aerial LiDAR data from the Durmid Hill Region. The location is shown by the yellow box in Fig. 1. Here the data is plotted at a rotated angle. White crosses show the location of targeted field observations. The red circle and arrows show the location and approximate look direction of the photographs in Fig. 11a,b, and d. The red box demonstrates the approximate location of panel (c). The curvilinear feature in the top region of the Figure is Bertram mine. The SSAF zone and Salton Sea are labeled. Note the tight folding with the some fold axis oriented northeast southwest, an orientation perpendicular to the SSAF and Salton Sea shoreline. The folding tightness changes markedly approaching the shoreline.

of the overlying sedimentary layers (*Kell, 2014*).

The eastward dip and thickening of layers observed in both of the MCS profiles, lines 7 and 19, suggests a dip-slip component along a vertical to westward dipping fault. Motion on the hanging wall along such a fault would create increased accommodation towards the fault and a northeast dip of the reflectors. The divergence of the layers indicate syn-depositional deformation (e.g., Fig. 3.2). The sections of gas near the eastern edge of MCS lines 7 (Fig. 3.2b) and 17 (Fig. 3.5) could be evidence for a fault (STF?), or permeability pathway along which fluids could migrate. Such observations are consistent with a fault structure between approximately 10 km along-track distance, and the shoreline of the Salton Sea (Fig. 3.2b).

Babcock (1974) performed a geologic field study of the Durmid Hill area (Fig.

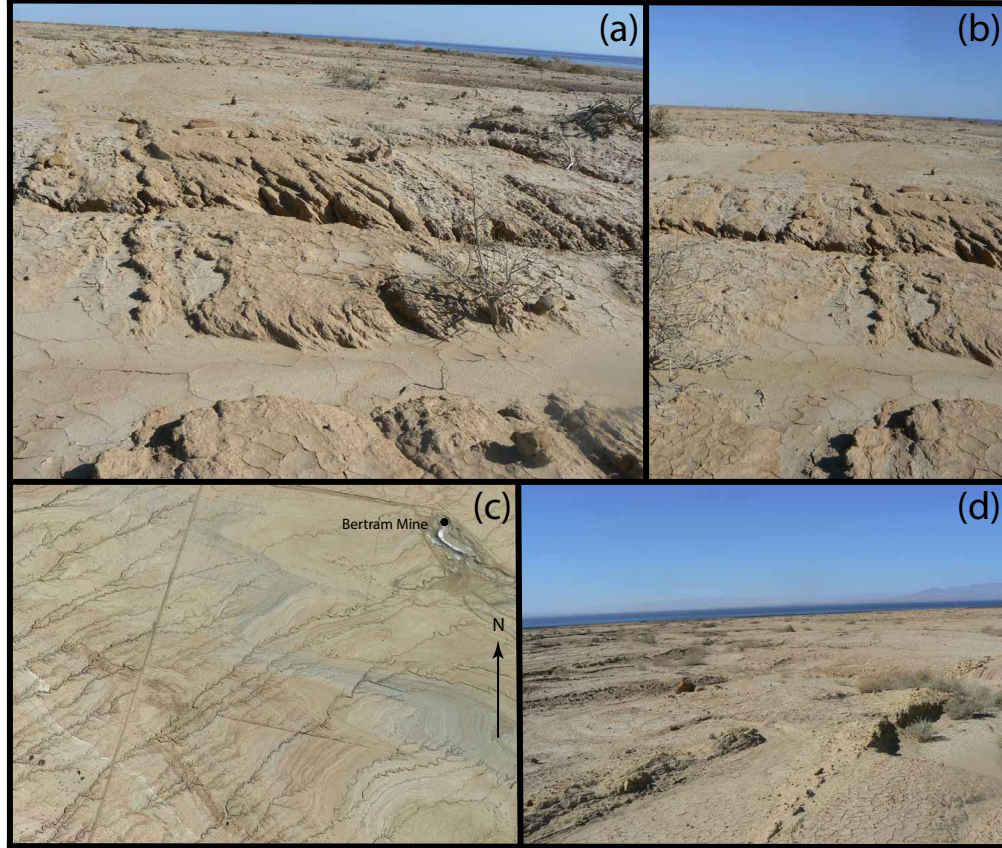


Figure 3.11: Photos from imagery, and the field. The location and look direction of the photos in panels (a), (b) and (d) are shown by the red circle and arrows in Fig. 10. Their look directions are slightly different. (a) Beds dip to the southwest, towards the Salton Sea shoreline. (b) The folding is much gentler near the sea, with folds having a long-wavelength characteristic. (c) Google imagery showing the folds as they approach the SSAF. (d) Beds begin to transition to a longer wavelength of folding, and dip to the southwest.

3.1), adjacent to the Salton Sea. Although there are no observations near Line 7 or Salt Creek due to the fact that Lake Cahuilla sediments bury any deformation and folding, evidence of faulting several kilometers to the south, closer to Line 17 is observed. Cross-sectional profiles show intense folding due to deformation associated with the SSAF zone, and all profiles show a consistent southwestward dip in the beds as the profile approaches the shoreline (Figure 8 in *Babcock (1974)*). The Borrego formation, a Pleistocene brackish water lacustrine deposit, is exposed throughout most of the region of the cross-sections, and younger Lake Cahuilla

sands are exposed to the northwest of this area.

The aerial LiDAR data collected in November 2010 (Fig. 3.10), along with field observation collected during March 2015 (Fig. 3.11) confirm the *Babcock* (1974) observations of folding. It appears that the SSAF controls the intensity of folding close to the fault zone. Approaching the shoreline, the folds begin to display a longer wavelength, and demonstrate a southwestward dip towards the shoreline. It appears these are no longer controlled solely by the SSAF. The left-lateral offsets and tighter folds observed closer to the SSAF might be suggestive of bookshelf faulting due to deformation between these two right-lateral strike-slip faults (SSAF and STF) and their splays. Nevertheless, the folding diminishes towards the southwest suggesting a decrease in compression away from the SSAF.

The images in Fig. 3.11 demonstrate the character of the beds in this location, and the southwestward dip towards the sea. Examination of these features in map view make it easy to observe the continuous spatial nature of the features. Images and data points collected in washes allow for a cross-sectional view of the beds and folding. These shoreline beds near the eastern shore of the Salton Sea show a southwestward dip. These geologic observations are consistent with extensional structure just to the southeast of the Salton Sea shoreline. Southwest of the shoreline and for the majority of the MCS lines, layers dip and thicken toward the northeast. On land just northeast of the shoreline, the layers dip to the southwest. This observation requires a structure within the Salton Sea to act as a control for the deformation. The collapse of these layers suggests that the structure is a transtensional strike-slip fault because the layers on both side of the fault dip towards it (Figure 4 in *Eisses et al.* (2015)).

Refraction data from Line 7 supports this hypothesis. The interface placed in the velocity model (Fig. 3.2) is intended to represent a variation in velocity or impedance contrast. A priori information exists for the western end of the profile, but is lacking in the eastern end. As such, the interface location in the eastern edge of the profile is more representative of a gentle gradient in velocity as opposed to a sharp contrast or jump. This is evident in the results of the models, observed in Figure 3.6. Regardless of location, the data require a low velocity zone in the

range of approximately 17 to 21 km along-track. Northeast of this low velocity zone, the velocities increase laterally, and the zone of higher velocities extends to the surface with a southwest dip. The low velocity zone straddles the region around the SSAF, as well as the region where a transtensional fault would be predicted based on stratal patterns. This low velocity zone could be due to a damage zone from the SSAF as well as the proposed Salton Trough Fault (STF). Northeast of the damage zone, velocities increase to over 3 km/s perhaps because of the older Borrego formation that exists in this area, which would be more compacted than Lake Cahuilla sands or lake sediments.

Unfortunately, the structure creating the observed deformation is not directly or poorly imaged by MCS data because of gas obscuring the reflectors and shallow water environments. Without direct evidence and imaging of the STF, other hypotheses were investigated to explain the extensional deformation in the strata. One such hypothesis is a southwestward-dipping SSAF with oblique, down-to-the-west motion. This would not be entirely surprising, as there are many real-world and laboratory examples of extension on the faults adjacent to a pull-apart basin. For example, the terminus of the Imperial fault in the Cerro Prieto basin appears to be in a transtensional environment (*Suarez-Vidal et al.*, 2008). Another example is observed along the Coronado Bank fault where extension is observed west of San Diego Bay pull-apart basin (*Maloney*, 2013). In addition, laboratory models (*Wu et al.*, 2009) show spatially sigmoidal patterns of extension on strike-slip faults adjacent to pull-apart basins, such that down-dip direction is orthogonal to the fault and towards the pull-apart basin. Extension from the pull-apart basin imprints along the adjacent strike-slip faults. This model however, would only explain the northeastern dip and extension in the reflectors and strata observed in the MCS data, and would not provide any mechanism for the southwestward dip in the beds on land. Furthermore, it does not explain the presence of the low velocity zone in the velocity models, and is in disagreement with previous interpretations of an eastward dip on the SSAF, proposed based on microseismicity, and strain rate from GPS and InSAR (*Fialko*, 2006; *Fuis et al.*, 2012). Finally, in following the line of evidence of extensional imprinting in a sigmoidal pattern, one

would expect to see greater subsidence or extension to the South, as the profiles approach the center of the pull-apart basin, and less extension to the north farther from the imprinting. MCS Line 17 (Fig. 3.5), located several kilometers south of Line 7, shows less extension than Line 7 and instead demonstrates some faulting within the profile, mantled by undeformed sediments. Even farther to the South, Line 16 (*Kell*, 2014) shows no evidence for extension and reveals a compressional strike-slip feature in the middle of the profile that is mantled by the divergent wedge described by *Brothers et al.* (2009). This is not consistent with predictions posed by models of pull-apart basin deformation described above.

Deformation on the STF is presumed to be long-lived due to the persistence of deformation observed in the MCS profiles, down to at least 1.8 seconds (~ 2 km) two-way travel time (TWTT). Surficial deformation observed on both the shallow 2010 and deeper 2011 MCS records relatively recent activity on the structure responsible for this geometry. The upper 0.05 seconds TWTT (~ 37.5 meters) appears undeformed. Reported sedimentation rates for the Salton Sea range between 2 cm/yr and 50 cm/yr (*Brothers et al.*, 2011). Given the above, yields an age estimate for the most recent event (MRE) on the STF of 75 to 1875 years ago.

To the south, the STF appears to change in nature and deformational style, from transtensional in the north of the Salton Sea as evidenced by Lines 19, 7, and 17, to transpressional south of Bombay Beach and in the Salton pull-apart (Line 16, *Kell* (2014)). To the north, it is difficult to discern any tectonic signal in the LiDAR data due to anthropogenic activity, therefore it is not clear if and where the STF continues onshore north of the Salton Sea. InSAR data (*Tong et al.*, 2013) show a faint trend of uplift, or motion towards the satellite, continuing onshore of the proposed STF location. The strike in this trend is similar to the expected strike of the STF, however it is noted in *Tong et al.* (2013) that this could be due to agricultural or anthropogenic activity. *Janecke* (2013) also proposes the existence of a structure west of the SSAF, the East Shoreline Fault, which is predominantly onshore; however, our proposed fault (STF) is projected to be in the Salton Sea, west of the shoreline.

Figure 3.12 is a schematic of the preferred hypothesis including the existence of the STF. The first panel describes the observations for the region, including geomorphic features as well as MCS data and geologic observations from *Babcock* (1974). The second panel describes the preferred hypothesis for the region – it shows the STF just southwest of the Salton Sea shoreline with folded strata between the STF and SSAF. The final panel is a subset of the second panel, showing in detail the MCS, refraction, and geologic observations. The seismic low velocity zone is caused by highly deformed material between the STF and SSAF, and MCS and geologic observations can be explained by the STF.

It is important to consider the implications of a previously unmapped extensional structure in this location. Currently, hazard in a given area quantified by ground motion prediction equations (GMPEs) is determined by a variety of factors, including the earthquake magnitude, dip of a fault, as well as style-of-faulting (*Bommer et al.*, 2003; *Campbell and Bozorgnia*, 2012). The presence of an extensional structure would affect the dip and style-of faulting considered in these equations, affecting the predictions from GMPEs for the region.

The STF could also significantly alter predictions from physics-based ground motion prediction methods. The STF could trigger or be triggered by rupture on the SSAF increasing the magnitude, or complicating rupture geometry. Additionally, radiation patterns of body and surface waves are a direct consequence of the strike, dip, and rake of the fault responsible for an earthquake (*Aki and Richards*, 1980). Triggering of the STF would alter the expected radiation pattern caused by an earthquake, in turn, affecting seismic wave propagation. This could potentially cause more amplification in sedimentary basins, and should not to be underestimated in Southern California as demonstrated by TeraShake (*Olsen et al.*, 2006). The San Bernardino, Chino, San Gabriel, and Los Angeles basins act as a waveguide into Los Angeles, further exciting waves that are trapped within these basins. Furthermore, three-dimensional models of rupture on thrust, normal and strike-slip faults (*Duan*, 2010; *Lozos et al.*, 2011; *Oglesby et al.*, 2000) show that the hanging wall of faults experience larger final displacements, as well as peak ground velocities (PGV), regardless of the style-of-faulting. When applied to

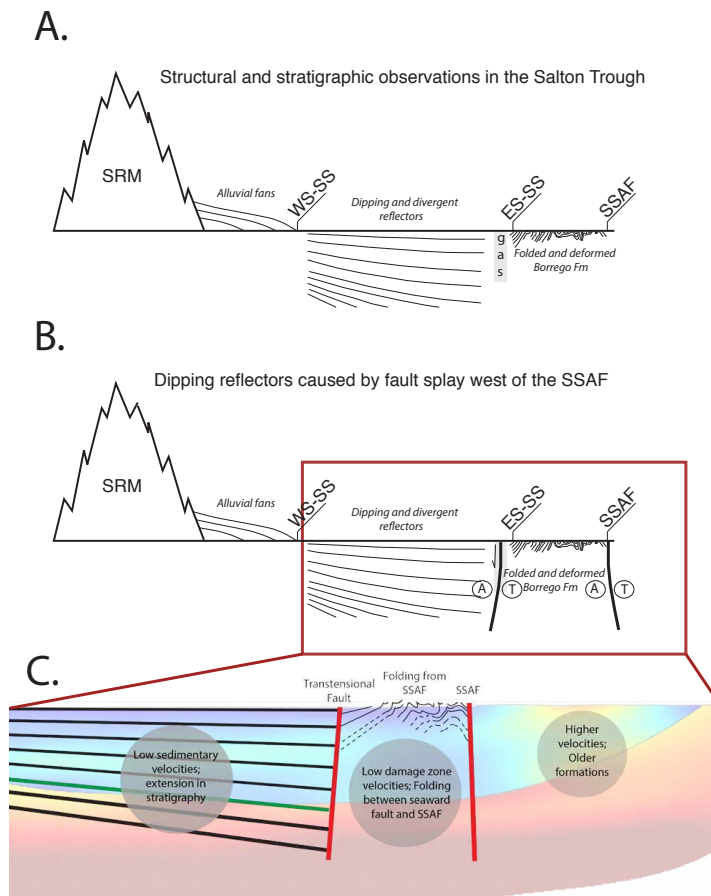


Figure 3.12: Schematic showing preferred hypothesis. SRM Santa Rosa Mountain block; WS-SS western shoreline of the Salton Sea; ES-SS eastern shoreline of the Salton Sea; SSAF Southern San Andreas Fault. (A) A diagram of the observations near Line 7. Southwest of Line 7 is the Santa Rosa Mountain block, and alluvial fans adjacent to it, up to the western shore of the Salton Sea. Reflectors in the sea dip and are divergent towards the northeast. Gas is present just west of the shoreline. East of the shoreline, the layers in the exposed Borrego Formation dip to the southwest, and are intensely folded closer to the SSAF. (B) Diagram showing the preferred hypothesis. A- away; T towards. Red box delineates the area of (C). A slightly southwestward-dipping transtensional strike-slip fault is present near the region of gas observed in the MCS lines. The SSAF is to the northeast of the folded Borrego formation, and dips slightly to the northeast. (C) Schematic showing the observations from MCS and refraction data. Green line in the strata on the left edge shows the high amplitude reflector used to constrain the velocity model interface. The zone between the STF and SSAF is damaged, and marked by a lower seismic velocity. Velocities increase to the northeast of the SSAF with an overall southwest dip.

the proposed geometry for the STF, this could suggest that PGVs and final displacements would be larger to the west of the fault. Most of these rupture models however, focus on thrust and strike-slip events and few on oblique events.

3.5 Conclusions

The marine active-source seismic reflection and refraction data presented here provide strong evidence for an extensional structure, the STF, near the eastern shoreline of the Salton Sea. Additionally, the strata and folding observed in the LiDAR data support the presence of the STF. It is proposed to be a transtensional fault west of the SSAF. This previously unidentified fault presents a new hazard to the region, and holds significant implications for fault models such as the Southern California Earthquake Center Community Fault Model (SCEC CFM), and consequently, models of ground motion prediction and SSAF rupture scenarios. Future ground motion simulation models, as well as GPS studies should consider this as a possibility.

3.6 Acknowledgments

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Chapter 4

Newport Inglewood Rose Canyon Fault Segmentation: Implications for Rupture Propagation

4.1 Introduction

The Newport-Inglewood/Rose Canyon (NIRC) fault zone is the easternmost component of the offshore faulting system in the Inner Continental Borderlands (ICB), and potentially poses a significant hazard to coastal Southern California as it lies within close proximity to some of the most densely populated regions of California and Baja, California (San Diego, Orange, and Los Angeles counties as well as Tijuana, Mexico). The ICB consists of mainly strike-slip fault structures, and includes some oblique right-lateral faults on reactivated Neogene structures remaining from margin reorganization (*Maloney et al.*, 2015). Together, the structures between the shoreline and San Clemente Island accommodate approximately 5–8 mm/yr of Pacific/North American plate boundary motion (*Bennett et al.*, 1996), approximately 0.5–2 mm/yr of which is partitioned along the NIRC fault zone (*Freeman et al.*, 1992). Geometry, location, and segmentation of the offshore elements of the NIRC fault zone are not well constrained. This study seeks to improve the characterization of geometry and segmentation of the NIRC fault

zone offshore between La Jolla and Newport Beach, and thus improve the current understanding of hazard in Southern California (Figure 4.1).

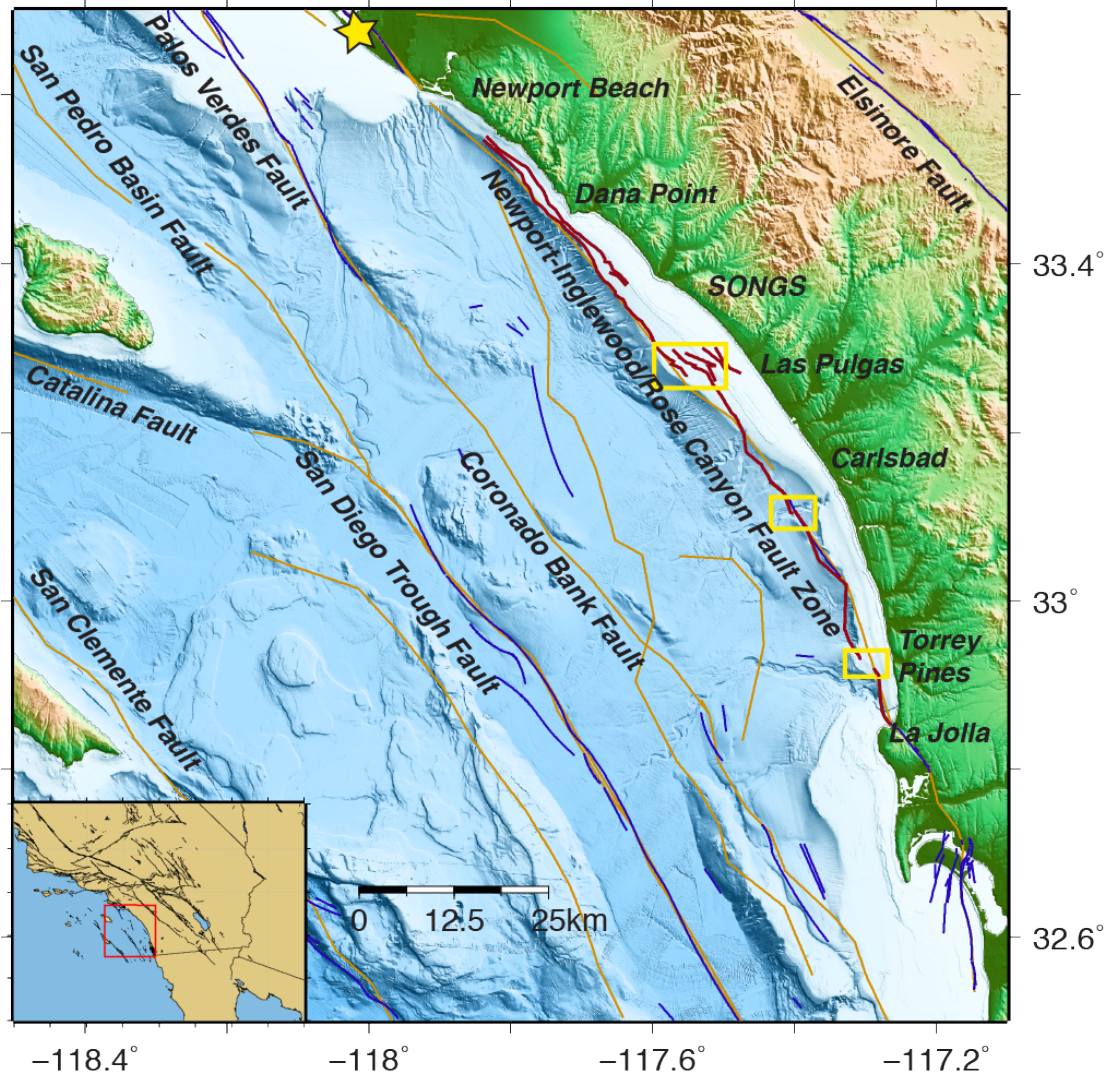


Figure 4.1: Regional map. The red box in the inset shows the location of this figure. Faults and landmarks mentioned in this paper are denoted on the map. The orange lines are the UCERF3 proposed rupture scenarios, blue faults are USGS mapped faults, and the red lines are this study's Newport-Inglewood/Rose Canyon fault zone mappings. Yellow boxes indicate the locations of the three stepovers discussed here, and the yellow epicenter is the approximate location of the 1933 Long Beach earthquake.

The NIRC fault zone continues north onshore from San Diego Bay to La Jolla, where it uplifts Mt. Soledad as the result of a left jog before shunting offshore

(Figure 4.1). The most recent event on the southern section of this fault, the Rose Canyon fault, is dated at 1650 $\pm$ 120 years, AD (*Lindvall and Rockwell, 1995; Rockwell, 2010*), following an estimated 5.5 kyr period of quiescence. Clustering is observed in 5 events prior to this, between approximately 6 and 9.3ka (*Rockwell, 2010*). The M_w 6.4 1933 Long Beach earthquake is the most recent event on the northern, Newport-Inglewood segment of the fault zone. This event occurred onshore near Compton and Newport Beach (*Hauksson and Gross, 1991*), and no surface rupture was observed (*Wood, 1933*). The epicenter from *Hauksson and Gross (1991)* is shown on Figure 4.1.

Onshore, in the south, the slip rate is constrained from trenching studies in Mission Beach and Mt. Soledad (*Lindvall and Rockwell, 1995; Rockwell, 2010*). In these locations, the slip rate is estimated at 1.0–2.0 mm/yr. The most recent event has approximately 3 m of slip on one strand (*Rockwell, 2010*). *Grant and Rockwell (2002)* hypothesize that this could have been part of a larger rupture including the Agua Blanca fault to the south in Mexico, or perhaps some offshore segments of the NIRC fault zone. To the north, *Grant et al. (1997)* estimates the slip rate on the Newport-Inglewood fault to be 0.35–0.55 mm/yr based on Cone Penetration Tests (CPTs), and *Freeman et al. (1992)* propose a rate of 0.5 mm/yr based on oil well logs, CPTs, borings, and seismic reflection data.

Offshore, slip rates on the NIRC fault zone are difficult to determine due to the lack of geodetic and core data as well as piercing points. No historic earthquakes have been documented on the offshore NIRC fault segments. Although past studies have described the NIRC fault geometry and segmentation, seismic survey data is sparse and there remains a dearth of data on or close to the continental shelf resulting in gaps in the fault mapping. *Hogarth et al. (2007)* observes a left step in the fault just after it moves offshore north of Mt. Soledad. *Ryan et al. (2009)* describes the fault strike on various segments from La Jolla/Mt. Soledad to Newport Beach, as well as the youngest age of deformation on the fault. They suggest 3 main segment boundaries, by Del Mar/Torrey Pines (as noted by *Hogarth et al. (2007)*), by Carlsbad Canyon (defined by a change in strike), and by Las Pulgas/San Onofre. They note, however, that it is often difficult to care-

fully map shallow deformation due to overprinting by the seismic source signature. Observations of dip change along-strike are also included in this study.

Seismicity offshore provides additional information regarding the fault geometry and state of stress. *Magistrale* (1993) analyzed a swarm of earthquakes that occurred near the southern NIRC segment in San Diego bay between 1985 and 1987. In this region, the NIRC strikes NNW and dips to the southwest ($\sim 70^\circ$). *Magistrale* (1993) found that these events occurred in a southwestward-dipping structure, though the focal mechanisms indicate slip on a northeastward-striking structure. He proposed that these clusters were due to events on northeasterly striking faults from Point Loma that intersected with the southwestward-dipping NIRC fault plane, and that the occurrence of these events indicated a change in stress on the fault. *Grant and Shearer* (2004) analyzed microseismicity offshore using a method that improves the relative locations of events within clusters. This approach increases the reliability of the clusters' spatial trends and alignments. They focused their attention on two main clusters that correlate with mapped NIRC fault traces within the events location uncertainty: one cluster 10 km north of Oceanside in 1981, and a second cluster near Newport Beach in 2000. Both clusters occurred on a NNW striking, nearly vertical fault plane, consistent with previous mapping of the NIRC fault zone.

The offshore NIRC fault zone is much less studied than the onshore segment. This study queries data sets of increased density and nested resolution to improve the constraints on the NIRC fault zone location, geometry, segmentation, and most recent episode of deformation. An important consideration for hazard analysis is whether fault segments in close proximity to each other can link up during coseismic rupture and generate a larger event. *Wesnowsky* (2006) studied patterns of through-going rupture at strike-slip fault steps, from a compilation of historical earthquakes, to determine the likelihood that an event could rupture through a stepover of given width and tectonic regime. He found that regardless of tectonic regime (transpressive or transtensional), events were significantly more likely to rupture through a stepover boundary of width 3 kilometers or less. No events in the database ruptured through stepover boundaries with widths 5 kilometers or

greater. In mapping segment boundaries and applying observations such as these, this study seeks to understand the maximum possible magnitude on the offshore segments. This will improve the current understanding of hazard for the coastal regions.

4.2 Methods

Fault imaging and mapping were performed with analysis of 4 nested resolutions of seismic reflection data, as well as high resolution (25m) multibeam bathymetry data for understanding the geomorphology of the fault system. Seismic reflection data included a 1979 Chevron dataset reprocessed by Geotrace, a 2006 USGS Single Channel Seismic (SCS) dataset (*U S Geological Survey (USGS) et al., 2006*) reprocessed in-house (details below), acoustic Compressed High Intensity Radar Pulse (CHIRP) data collected between 2006 and 2009, and newly acquired 2D Multi Channel Seismic (MCS) data from August and December 2013. Figure 4.2 contains a map of the location of these surveys. The 1979 Chevron MCS data were acquired with a 96-channel hydrophone streamer with 33.5 m hydrophone receiver spacing and shot spacing. This yielded 48 fold data with a common midpoint space of 16.75 m of separation. The source was a 49.2 l (3000 cubic inch) airgun array. The penetration depth of this data is ~ 2 seconds Two Way Travel Time (TWTT), or 2 to 3 km depth. The 2006 USGS SCS data were collected with a single channel receiver and a 2 kJ mini-sparker source. Reflectors are resolvable to ~ 1 second TWTT, or ~ 1 km. Reprocessing details will be discussed below. All CHIRP surveys were conducted with the Scripps Institution of Oceanography's Edgetech profiler, with coincident transducer and receiver. The instrument was operated using a 50 ms swept pulse of 0.7 – 3.0 kHz or 1 – 6 kHz pulse depending on sediment character, resolving stratigraphy to approximately 50m depth. The 2013 MCS data were collected offshore on the R/V New Horizon using a 2 kJ three tip EG&G 402-7 sparker source and 48 channel streamer, with a group spacing of 6.25 m and 3.125 m shot spacing, allowing reflectors to be resolved to approximately 1.5 sec TWT, or 1.5 km depth. The location of each of

these surveys is shown in Figure 4.2.

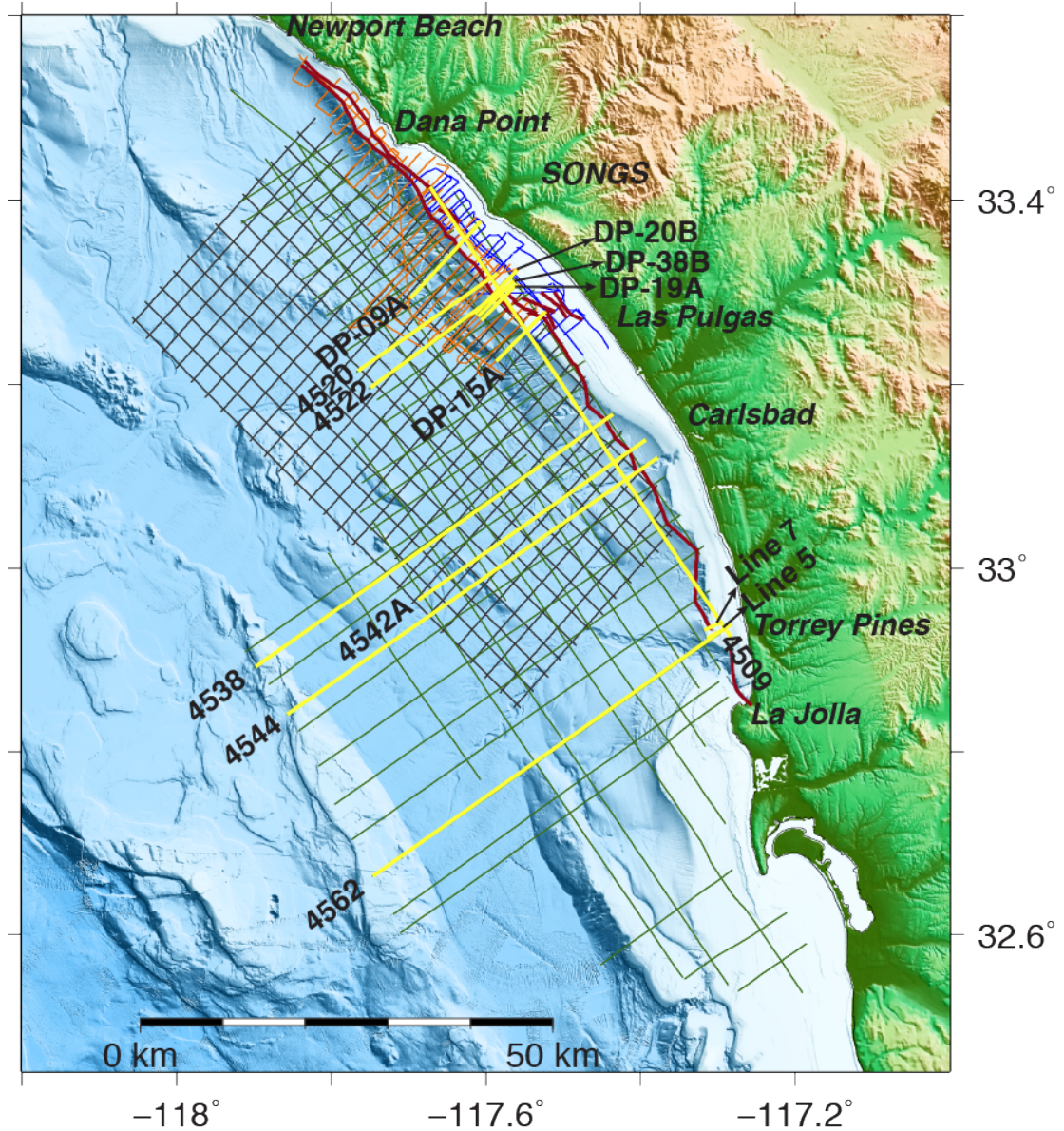


Figure 4.2: Map of survey lines included in this study. Green lines are the 1979 Chevron lines, black are the 2013 MCS lines, orange are the 2006 SCS USGS lines, and blue are the CHIRP lines. The red line denotes the NIRC fault mapped in this study. Landmarks are noted on the figure. Lines presented in this paper are highlighted in yellow and labeled.

The CHIRP and USGS data image the top strata and resolve the most recent episode of deformation. The Chevron data image the deeper structure and

interconnectivity of splays, and the 2013 sparker MCS data provide high-resolution imaging of intermediate depths. Some lines in each of these datasets intersect the NIRC fault zone, though only the CHIRP and USGS data image the fault zone on the widest section of the shelf, from Las Pulgas to Newport Beach. Combining these datasets provides a nested resolution with unparalleled density to date on the NIRC fault zone.

The 2013 sparker MCS data were stacked at 1500 m/s, and further processing included post-stack f-k migration using a nominal water velocity of 1500 m/s. The Chevron data were processed by Geotrace, using a hybrid multiple suppression scheme (Surface Related Multiple Elimination (SRME) plus Radon filtering), trace interpolation in shot and receiver space, and prestack time migration (PSTM).

The 2006 USGS data contained moderate levels of noise and had strong multiples, thus a few reprocessing steps were applied to improve clarity, reflector continuity, and aid in interpretation. To perform heave removal, a robust spline was fit to picked seafloor arrival times, and then variations from this spline removed from the arrival times to adjust each trace and align reflectors.

Noise was present in these data due to contamination of energy from destructive interference from the source and receiver ghosts in the recordings, reducing clarity in the seismic sections. This interference is visible as a notch in the frequency domain, corresponding to the wavelength of the two-way travel time of sea surface to receiver or source. The next step in the reprocessing was to use inverse filters to compensate for this acquisition impulse response. A single inverse filter in the frequency domain was sought to remove these notches and produce a compressed, zero phase source signature. ?

Multiple removal was performed using a 1D surface-related multiple elimination scheme, (*Berkhout and Verschuur, 1997; Verschuur and Berkhout, 1997; Riley and Claerbout, 2012*). To perform this, a filter is selected in an iterative least squares sense by minimizing the energy in the estimated primary reflections. It is then applied to the data. The recorded pressure at the receiver, P , can be represented by the following equation:

$$P = P_0 + P_0[S^+]^{-1}R^-[D^-]^{-1}P, \quad (4.1)$$

where P_0 is the primary reflections, S^+ is the source wave field and source ghost, R^- is the sea surface reflection, and D^- is the instrument response and receiver ghost. Equation 4.1 can be simplified to

$$P = P_0 + P_0AP, \quad (4.2)$$

where the second term in Equation 4.2 represents the infinite series of all the sea-surface multiples, M_0 :

$$M_0 = P_0AP, \quad (4.3)$$

and

$$A = [S^+]^{-1}R^-[D^-]^{-1}, \quad (4.4)$$

where A is the filter. For each trace, A is estimated iteratively by minimizing an estimate of P_0 , P_0^e , with the L1 norm. P_0 , the actual primary response, remains fixed, however the estimate, P_0^e , changes from iteration to iteration. In this sense, this method can fail in regions where there is energy from high amplitude primaries, as minimization may occur on the actual primaries as opposed to the multiple.

Once estimated, A is subtracted from the data to remove the multiple, in theory leaving only the primary reflections remaining. An assumption here is that the energy of the reflections has near vertical incidence. Thus, the method works well in relatively flat areas but has sub-optimal results on steeper areas such as the continental slope. Figure 4.3 shows an example of the difference between original and reprocessed data that exemplifies the filter performance.

Finally, coherency filtering was applied to the data to improve reflector continuity. This filter operates with a sliding time window, estimating weights to apply to the time window segment based on a convolution of the data and the sinc function. For these lines, the coherency filter is applied on a patch basis, where patches consist of 250 traces and 500 time samples, with patch overlaps (Yilmaz, 2001). An example of this reprocessing is shown on USGS line DP-09 (Fig. 4.3).

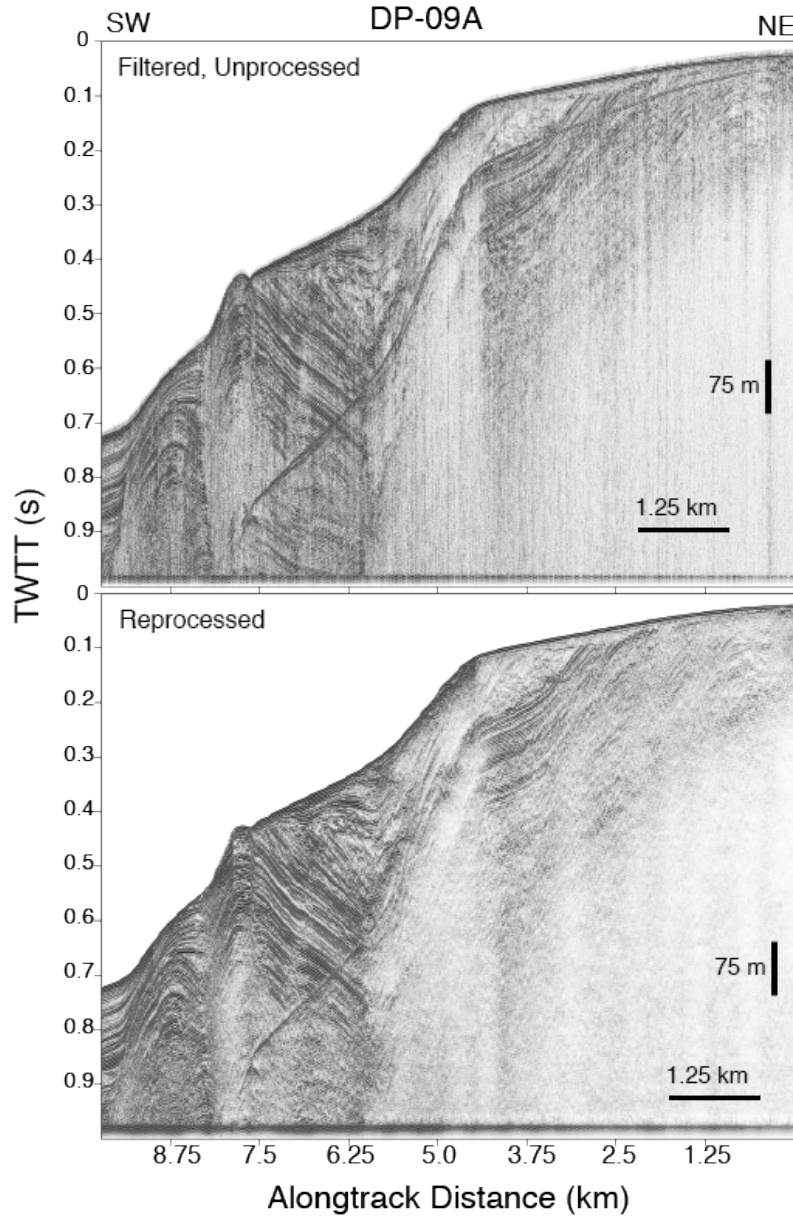


Figure 4.3: An example of the USGS reprocessing, on line DP-09A. The top shows the original bandpass filtered data, and the bottom panel shows the reprocessed data. Note that the multiple has been suppressed in all locations except the steeply-dipping regions. The continuity of reflectors has been improved and the signal to noise ratio.

Stress change modeling was performed using the USGS package Coulomb 3 (*Lin and Stein, 2004; Toda et al., 2005, 2011*). Here, the 3D faults interpreted from the reflection data were simplified to planes with strike and dip determined as the

average of the observed faulting surface. In this modeling approach, source faults are assigned slip, and impart stress on the surrounding medium as well as on other receiver faults with prescribed location, strike, and dip. Calculations are made in a two-dimensional elastic half-space, using uniform isotropic material properties, and following the method of *Okada* (1992). For this study, the total coulomb stress change was calculated treating each fault segment individually as a source fault and then determining the stress change on the other receiver fault segments. A total of 20 computations were performed to model the stress changes on each receiver fault geometry. The computational domain was a cartesian grid of 0.5 km in x and y and 1 km in depth. The material properties were prescribed with a Poissons ratio of 0.25, static frictional coefficient 0.4, and Youngs modulus of 75 GPa. This last parameter was derived from the Poissons ratio, and a shear modulus of 30 GPa. The shear modulus was derived from a one-dimensional profile of compressional and shear wave speed near Oceanside, from the 3 dimensional structure model for Southern California, SCEC CVM-H (*Shaw et al.*, 2015). In each model, 2 meters of right-lateral slip was prescribed on the source fault.

4.3 Results

The seismic data analysis identified three main segment boundaries or steps, and five predominant strands or segments in the NIRC fault zone. These segment boundaries are characterized by a stepover width great enough to be considered a separate boundary as opposed to a splay (greater than 100 – 200m wide), a change in the recency of deformation along-strike, or a significant change in strike. They occur near La Jolla or Torrey Pines, Carlsbad Canyon, and San Onofre (locations shown by yellow boxes in Figure 4.1). The southernmost stepover occurs near La Jolla and Torrey Pines. Here, the NIRC fault zone jogs to the left after moving offshore north of Mt. Soledad. This jog creates a popup structure by Torrey Pines, and occurs at the location where the shelf is widest in the southern region, north of La Jolla canyon. The southern segment before the popup is from here on referred to as the La Jolla segment, and to segment the north as the Torrey Pines segment.

The popup is imaged in the deeper Chevron data, as well as the shallow CHIRP data. Figure 4.4 shows the popup as observed in the Chevron data, down to approximately 1.5 km depth. Line 4562 crosses the NIRC fault and is seen to depth on the section; however, it is blocked from view in this fence diagram because of the intersection with Line 4509 (Fig. 4.4). This figure demonstrates the uplift and antiformal structure in the deeper strata. In contrast, Figure 5 presents direct imaging of the NIRC fault in the CHIRP data on the shelf. The top panel in Figure 4.5 shows uplift on the fault scarp on CHIRP line 7. The bottom panel shows a small pull-apart basin that is superposed on the larger popup structure (Figure 1 in *Hogarth et al. (2007)*). These data also image two antiforms along the outer shelf within the popup structure, with resolution to 50m subbottom depth. This stepover is approximately 2 km in width, as noted on the map view in Figure 4.4.

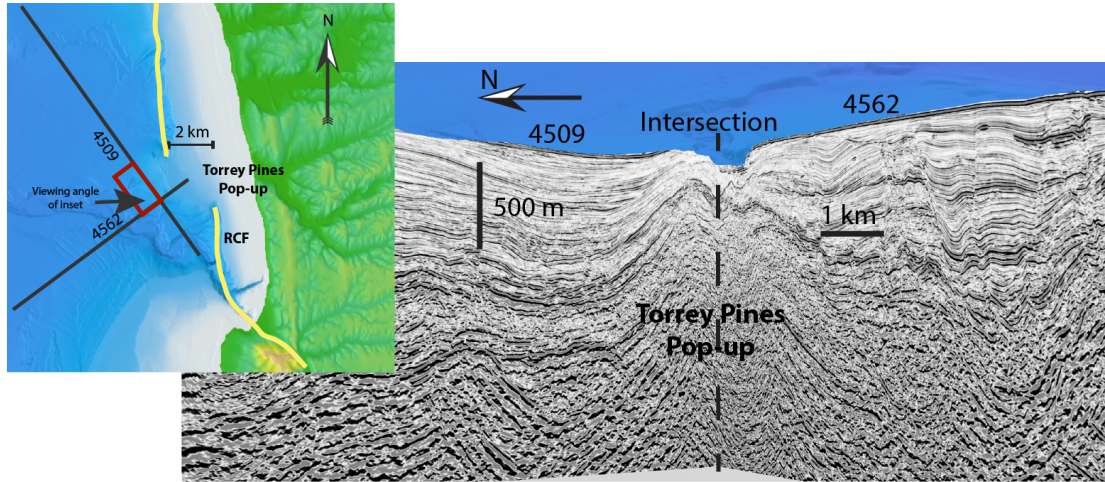


Figure 4.4: The Torrey Pines segment boundary. The map view at the left shows the location of the pop-up, and the location of the Chevron lines shown in the figure. The red box shows the location of the figure, and the arrow shows the viewing angle. The yellow line is the NIRC trace. The image on the right shows the pop-up in the deeper Chevron data created by the stepover, with a horizontal look angle towards the intersection of the line. The dashed black line shows the intersection of Chevron lines 4509 and 4562 for clarity. These data extend to approximately 2km depth. Note the reflectors are deformed in an anticlinal formation at the pop-up structure. The Rose Canyon is observed both in the seismic reflection and bathymetry data.

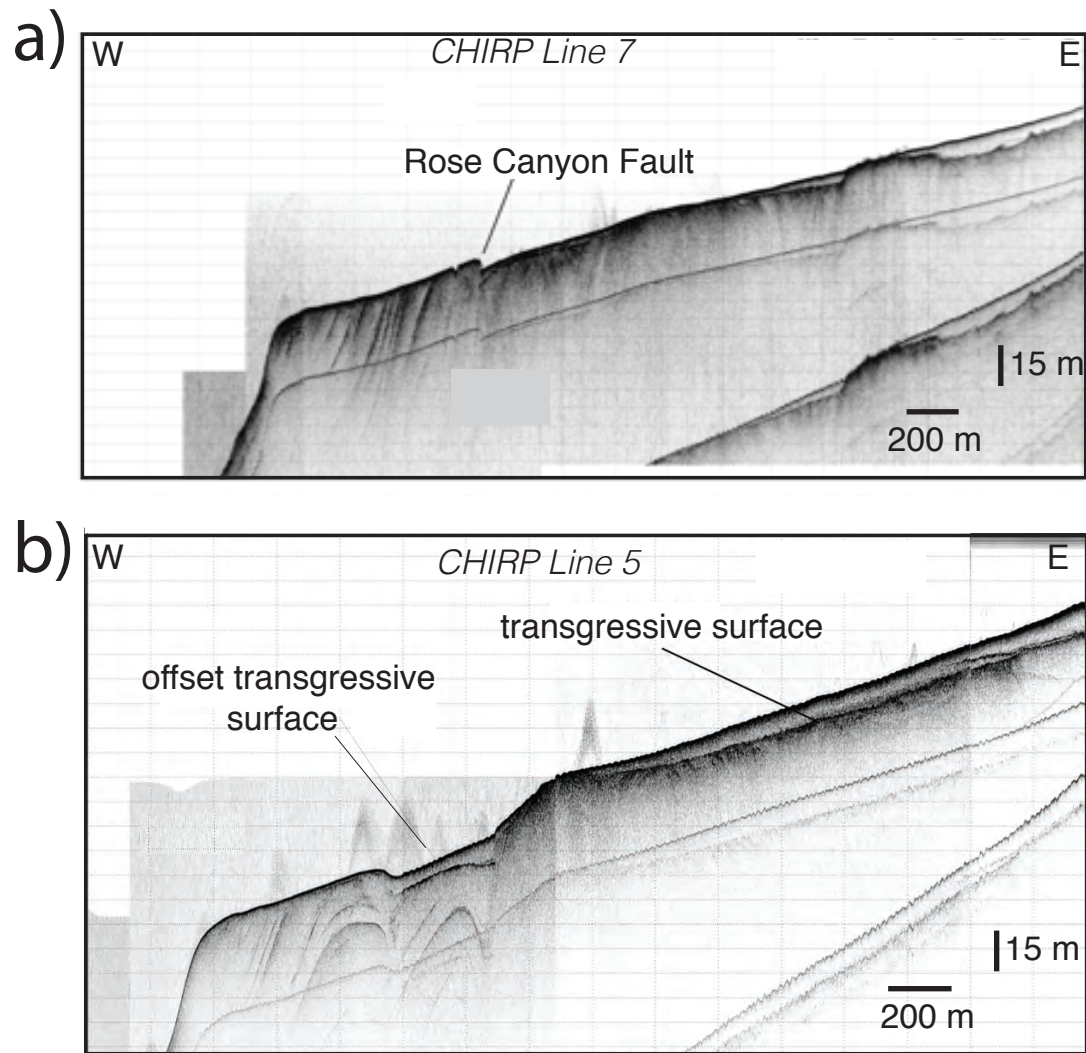


Figure 4.5: High-resolution image of the Torrey Pines pop-up, from CHIRP data on the shelf (Figure 1). a) Line 7 images the Rose Canyon fault, and demonstrates the seafloor deformation observed in the southern NIRC fault zone. b) Line 5 images a basin formed by NIRC splays, from a distributed zone of faulting within the stepover.

The second major stepover or segment boundary is by Carlsbad Canyon, and separates the Torrey Pines and Carlsbad Canyon segments. This stepover is characterized by a slight westward step, minor change in strike and dip, and most notably, by a change in the recency of deformation observed in the seismic data. South of the stepover, the lines image deformation of the seafloor, or deformation mantled only by a thin package of sediment. North of the stepover, the most

recent episode of deformation steps down in the seismic data. These observations are demonstrated by Figure 4.12, in which Chevron line 4544 is the northernmost line to image the Torrey Pines segment. Chevron lines 4542A and 4538 image the Carlsbad Canyon segment. Figure 4.12 shows both the NIRC fault (marked by black lines) and Carlsbad trend (marked by green lines), described in *Ryan et al.* (2009). The red marks the location of the seafloor. North of line 4544, the NIRC fault steps to the west, and the dip changes from a slight eastward dip, to a slight westward dip. Additionally, the thickness of the sediment package mantling the fault increases to the north. This stepover is less than 0.5km in width, and is located in the only region where the NIRC fault zone is not adjacent to the shelf break (Fig. 4.1).

The third major stepover is by San Onofre, on the widest section of the shelf between La Jolla and Newport Beach. Here, the Carlsbad Canyon fault segment dies away to the north, and the westward Camp Pendleton segment dies to the south as the two overlap (Fig. 4.7). The Carlsbad Canyon segment exhibits a curvilinear feature to the northwest, forming an anticlinal feature on the shelf, believed to be responsible for forming the wide shelf. This antiformal structure traps sediment from the east. These observations are presented in Figure 4.7, showing three USGS lines, DP-19A, DP-38B, and DP-20B. In this figure, the red lines again represent the seafloor on each line. The brown line denotes the Carlsbad Canyon segment, curving to the northwest, and the green is the Camp Pendleton segment, cross-cutting the antiformal structure. It should also be noted that here, the Camp Pendleton segment appears to control the location of paleochannels, marked in blue in Figure 4.7. The faults and antiformal structure may also be observed in 3D MCS data on the shelf, as presented in *Holmes et al.* (2014). These two segments are separated by approximately 1.5 km.

Farther north of this stepover, the Dana Point segment strikes parallel to the Camp Pendleton segment and dies away towards the San Onofre stepover. Both the Camp Pendleton and Dana Point segments approach Newport Beach onshore (Fig. 4.1), and are spaced approximately 200m to 2 km apart, depending on the location along-strike. These do not merge at depth, within the depth resolution of

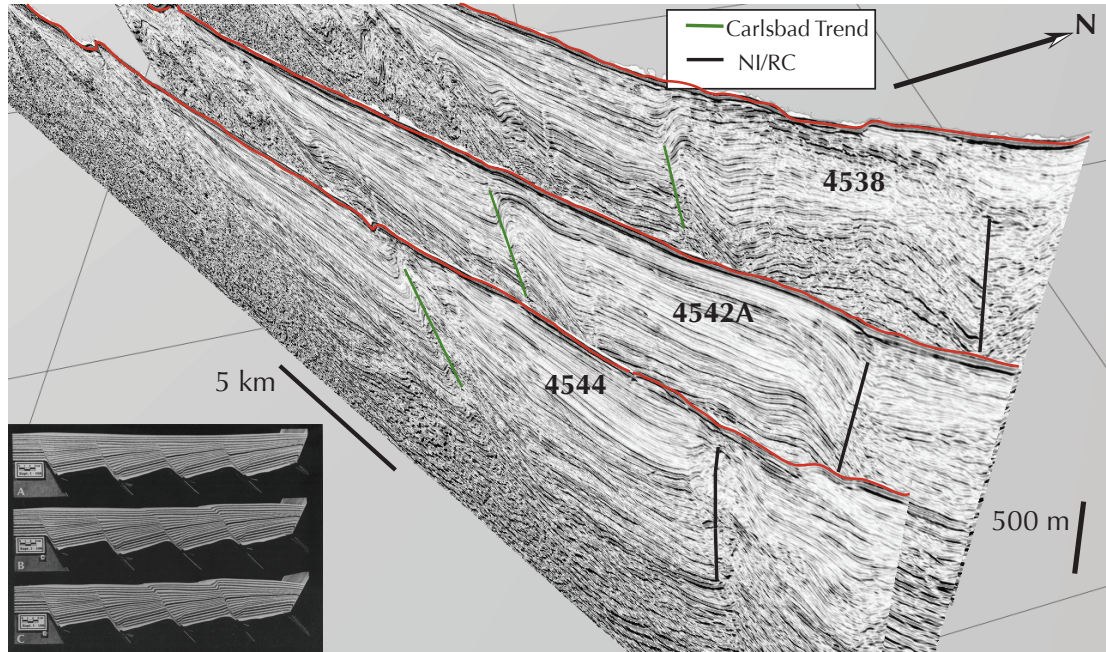


Figure 4.6: The second segment boundary, by Carlsbad Canyon. This stepover is characterized by a slight westward-step, as well as a change in the recency of deformation. The north direction is marked, the three Chevron MCS lines cross the Carlsbad trend and farther east the NIRC fault zone. The red line denotes the seafloor; black is the NIRC fault, and green is the Carlsbad trend. Line 4544 is on the Torrey Pines segment, and lines 4542A and 4538 are on the Carlsbad Canyon segment. Note that deformation extends almost to the seafloor on 4544, and is progressively deeper to the north. The NIRC geometry also transitions from a slight eastward dip, to a more westerly dip. The inset on the bottom left shows an example of tectonic inversion from *Buchanan and McClay* (1992), demonstrative of the process occurring on the Carlsbad Trend here.

the seismic profiles (up to ~ 2 km); they may, however, coalesce at greater depths and cannot be observed with these data.

Figure 4.8 presents mapped locations of NIRC fault zone based on the nested seismic surveys. The various colors and symbols denote separate segments or strands mapped, with the five main named segments labeled in the legend: the La Jolla, Torrey Pines, Carlsbad Canyon, Camp Pendleton, and Dana Point segments. The short splays near San Onofre may continue to the north or south, but the data employed in this study cannot resolve them any further; thus, they are not discussed at length or included in stress modeling in this study. It should

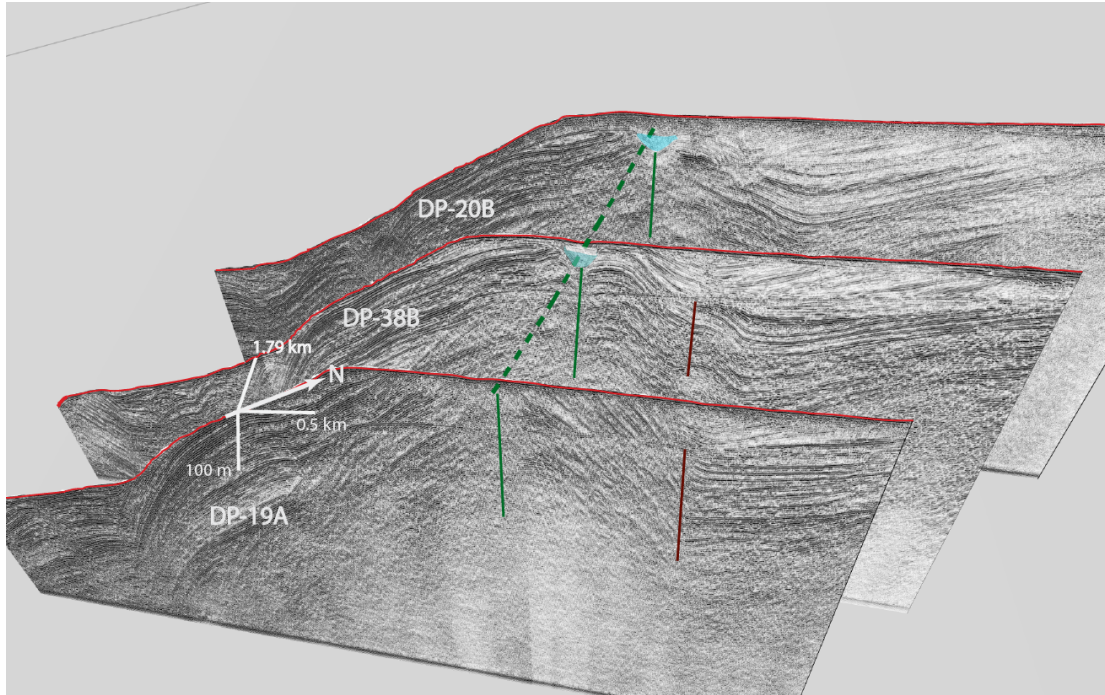


Figure 4.7: Third segment boundary is located offshore San Onofre. USGS lines, DP-19A, DP-38B, and DP-20B are shown. North direction and scale are in white. The red and green lines show segments of the NIRC fault. The brown line is a curvilinear feature in the fault that curves to the northwest and creates the antiformal structure observed in the reflectors. The green dashed line shows the inferred structural trend between profiles. The location of paleochannels is highlighted in blue. Red lines denote the seafloor on each line.

be noted however, that this is the only known location where the NIRC fault zone is represented by such a large number of smaller splays, as opposed to being concentrated on one or two main strands. The strike of each fault varies even along each segment, and the segments exhibit a more northwesterly strike toward the north in the study region. Additionally, the segments define or follow the shelf edge for the majority of the margin. To the south of the Torrey Pine popup structure, the location of the NIRC fault zone is based on data presented in *Hogarth et al.* (2007).

Fault dip also varies significantly along-strike as well as between segments. Figure 4.9 summarizes the apparent dip mapped for each of the five main segments, plotted with the same color scheme as Figure 4.8. Short arrows indicate a near-

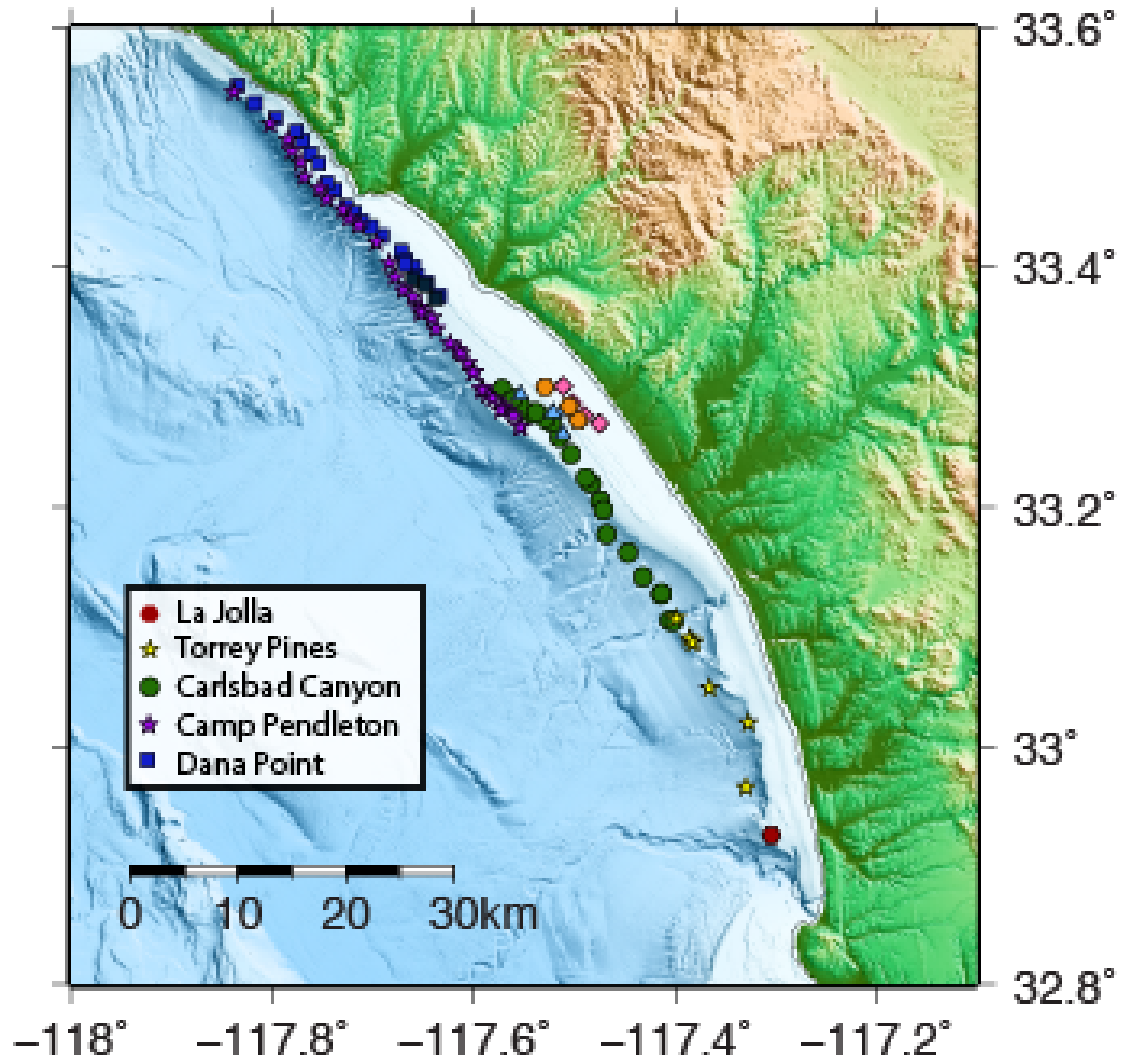


Figure 4.8: Locations of NIRC fault zone based on seismic data shown in Figure 4.2. The colors and symbols represent all mapped segments. The legend describes the main segments. Red hexagons: La Jolla segment; Yellow stars: Torrey Pines segment; Green circles: Carlsbad Canyon segment; Purple stars: Camp Pendleton segment; Blue squares: Dana Point segment. In the south, the La Jolla segment is mapped from geomorphology, as well as observations from *Hogarth et al.* (2007).

vertical dip, whereas longer arrows indicate a shallower dip. The dip shown here is apparent, as its magnitude is controlled by both the azimuth of the seismic line and fault trace. Some segments, such as Carlsbad Canyon, display a more consistent dip along-strike than others, such as the Camp Pendleton segment.

South of the Carlsbad Canyon stepover, the NIRC fault zone deformation

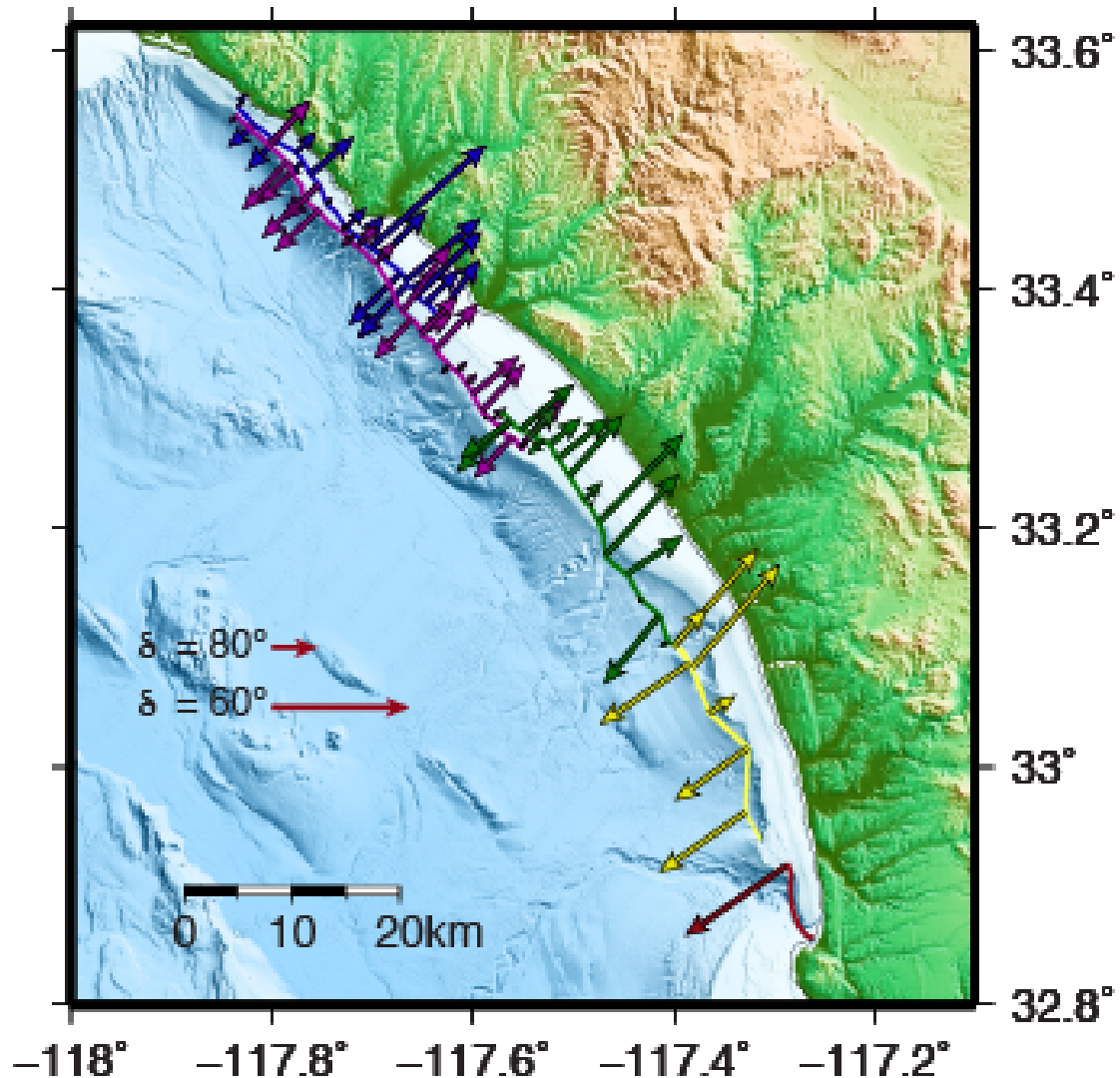


Figure 4.9: Map of apparent dips of the five main segments, from seismic lines crossing the NIRC fault zone. Red: La Jolla segment; Yellow: Torrey Pines segment; Green: Carlsbad Canyon segment; Purple: Camp Pendleton segment; Blue: Dana Point segment. Longer arrows indicate a shallower dip; no arrow or short arrows indicate vertical or near vertical dips. Some segments show a consistent dip; others vary along-strike.

extends to or close to the seafloor. North of Carlsbad Canyon, the deformation steps down into the sediment until Las Pulgas. From Las Pulgas to Dana Point, the deformation often deforms layers beneath the transgressive surface. In areas the transgressive surface shoals; these shoals correlate with the NIRC fault zone and the Cristianitos fault. Nevertheless, the preferred hypothesis is that these are

antecedent features are more resistant to erosion and do not record deformation of the transgressive surface (*Klotsko et al.*, 2015). North of Dana Point, the NIRC fault deformation offsets the transgressive surface (dated at $\sim 11 - 13$ ka) and in regions approaches the seafloor.

Models of total Coulomb stress change were conducted for each fault segment to develop a quantitative understanding of static triggering and through-going rupture across stepovers. As slip is imposed on a fault, a complex stress pattern is created surrounding the fault. Static stress changes are not a conclusive measure of likelihood of triggering across stepovers as dynamic triggering is often more significant, however it provides a more quantitative measure of triggering when compared to purely empirically-based metrics. Earthquake events on source faults were modeled with two meters of dextral co-seismic slip. Fault geometry was assumed to be a simple plane with the average measured strike and dip of the fault segment.

Former studies considered through-going rupture on the basis of observed surface stepover width, and did not consider dip (*Wesnowsky*, 2006). Here, modeling results are presented regarding the potential effect of fault dip on rupture propagation at stepovers. Figure 4.10 demonstrates some of these results. The La Jolla segment exhibits a dip of approximately $67-70^\circ$ WSW. The total coulomb stress change on the Torrey Pines segment from deformation on the La Jolla segment is small, given the observed dips of each of these segments (Figure 4.10a). If the La Jolla segment were assumed to be vertical, however, the Torrey Pines segment would experience a significant increase (greater than 5 bars) in stress (Figure 4.10b).

These tests were conducted for each of the five strands, to examine how each source fault rupture impacts adjacent receiver faults. Here, three scenarios of rupture are presented to demonstrate a variety of end-member situations and their resulting event magnitudes. In scenario I, rupture initiates on the La Jolla segment. The four panels in Figure 4.11 show the stress change on a receiver fault (white bar) from adjacent source faults (yellow bar), with rupture propagating north. Figure 4.11a shows the main increase in Coulomb stress is east of the

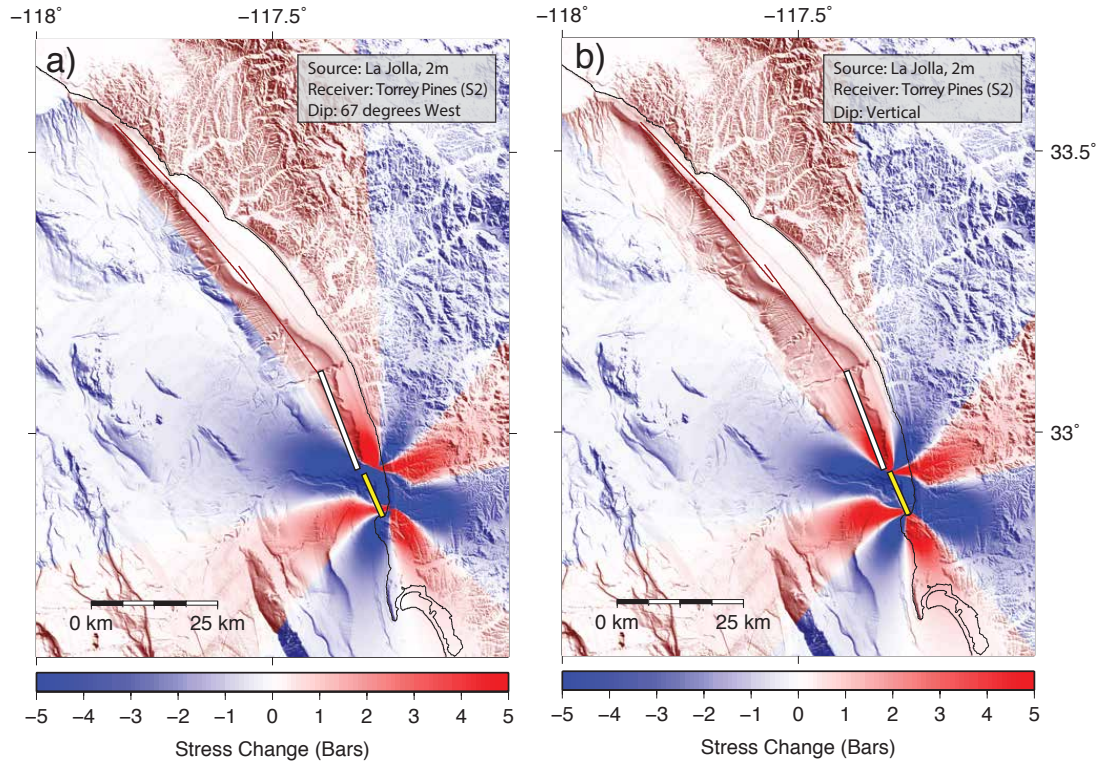


Figure 4.10: Total coulomb stress change from 2m of slip on a source fault (marked by yellow bar) onto receiver fault (marked by a white bar). a) Stress change onto the Torrey Pines segment, from 2m of displacement on a dipping La Jolla segment (dip as observed in data). Note that the stress increase on the Torrey Pines segment is minimal. b) Stress change onto the Torrey Pines segment with 2 m of displacement on a vertical La Jolla segment. If the La Jolla segment were vertical, the Torrey Pines segment would be in the center of the lobe of increased stress.

receiver fault. In fact, the southern terminus of the Torrey Pines strand is in an area of reduced or no Coulomb stress change. Only a slight increase in Coulomb stress is observed on the Carlsbad Canyon receiver fault in response to the rupture of the Torrey Pines source fault (Fig. 4.11b). Rupture on the Carlsbad Canyon source fault causes the maximum increase in Coulomb stress to be slightly east of the Camp Pendleton receiver fault (Fig. 4.11c) and the maximum being slightly west of the Dana Point receiver fault (Fig. 4.11d).

The scenario II is characterized by rupture initiation on the middle Carlsbad Canyon segment (Fig. 4.12). The source and receiver fault color scheme remains

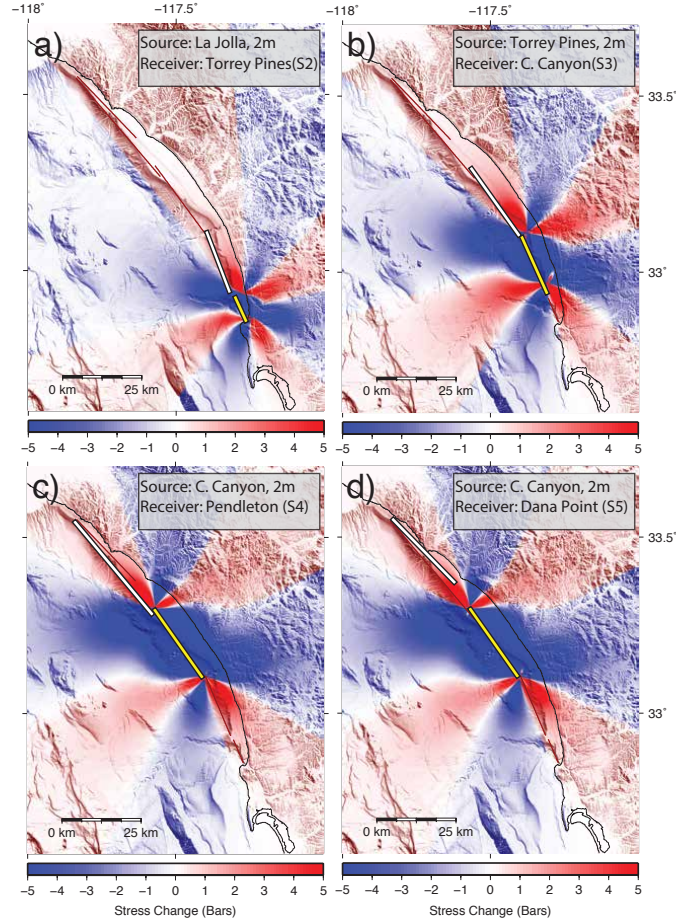


Figure 4.11: Rupture scenario I - Coulomb stress change from 2m of displacement on source faults starting in the south. Yellow bars indicate the source fault, and white bars indicate the receiver fault. S2, S3, S4, and S5 represent the numbers of each receiver faults. a) Total stress change on the Torrey Pines receiver fault from the La Jolla source fault. The Torrey Pines receiver fault (S2) is on the fringe of the lobe of increased stress. b) Total stress change onto the Carlsbad Canyon receiver fault (S3) from the Torrey Pines source fault (S2), which is on the fringe of the lobe of increased stress. c) Total stress change onto the Camp Pendleton receiver fault (S4) from the Carlsbad Canyon source fault (s3), the receiver fault is offset slightly to the west from the maximum increased Coulomb stress. d) Total stress change onto the Dana Point receiver fault (S5) from the Carlsbad Canyon source fault (S4), also offset from maximum Coulomb stress increase but to the east.

the same as Figure 4.11: the source fault is marked in yellow in each quadrant, and receiver in white. In this scenario, all other adjacent receiver faults (La Jolla, Torrey Pines, Camp Pendleton, and Dana Point) experience increased stress with

some up to 5 bars. The final scenario, scenario III, explores the stress change from rupture from north to south with rupture initiation on the Camp Pendleton strand (Fig. 4.13). The Dana Point receiver fault is entirely in the coulomb stress shadow when Camp Pendleton is the source fault (Fig. 4.13a). The Carlsbad Canyon receiver fault has both reduced and increased Coulomb stress; it is important to note the reduced stress is only along the northern terminus of the strand. Despite the strand being on the eastern edge of the increased stress, the central portion experiences a stress increase of almost 5 bars. When the Torrey Pines strand is the receiver fault and the Carlsbad Canyon is the source fault (Fig. 4.13c), the receiver fault is centered in the increased stress lobe. Likewise for the La Jolla strand when it is the receiver fault (Fig. 4.13d).

4.4 Discussion

These results imply that the fault segmentation not only controls margin architecture (e.g., shelf width, pop-structures, shoaling of transgressive surface), but potentially plays an important role in rupture propagation and earthquake magnitudes. Along this section of the margin, the shelf is widest by San Onofre. This appears to be caused by antiformal feature created by the NIRC fault, as well as sediments sequestered east of this feature. The location of paleochannels also appears to be controlled by fault location and the anticlines, as the faults provide areas of weakness, further eroded upon by these channels. Additionally, the shelf is narrowest by the Carlsbad Canyon stepover. This could be due to a landslide, perhaps triggered by an event on the NIRC fault. The geomorphology is consistent with this hypothesis (Fig. 4.1), though no tests have been investigated to provide supporting evidence.

This study finds, as did *Ryan et al.* (2009), that the local tectonic setting is often transtensional when the NIRC fault is more northerly striking, and transpressional when more northwesterly striking. For example, the NIRC fault is northwesterly striking in the region of the San Onofre stepover, where the antiformal structures are observed.

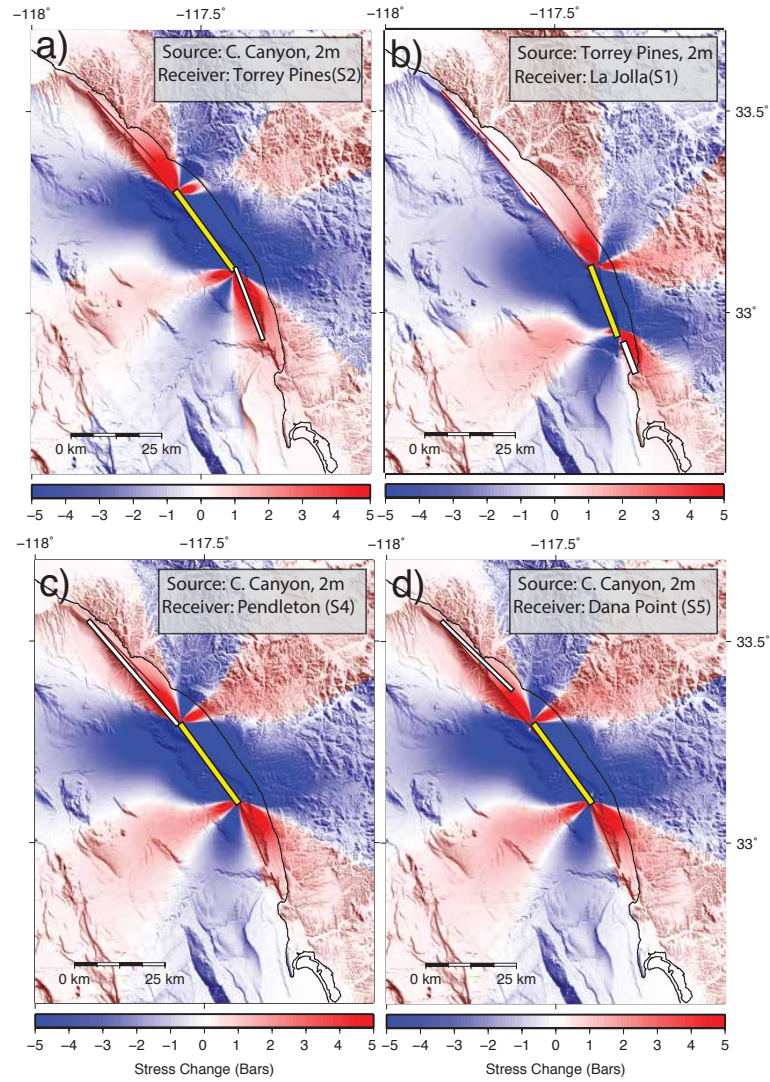


Figure 4.12: Rupture scenario II - total coulomb stress change from 2m of displacement on the Carlsbad Canyon and Torrey Pines source fault (marked by yellow bar) onto adjacent receiver faults (marked by a white bar). All receiver faults experience an increase in Coulomb stress in Scenario III a) Stress change on the Torrey Pines receiver fault (S2) from rupture on the Carlsbad Canyon source fault (S3). b) Stress change onto the La Jolla receiver fault (S1) from the Torrey Pines source fault (S2). c) Stress change onto the Camp Pendleton receiver fault (S4) from the Carlsbad Canyon source fault (S3). d) Stress change onto the Dana Point receiver fault (S5) from the Carlsbad Canyon source fault (S3).

The stepovers imaged in the nested seismic reflection data were 2 km in width or less. According to *Wesnowsky* (2006), there is a high likelihood that rup-

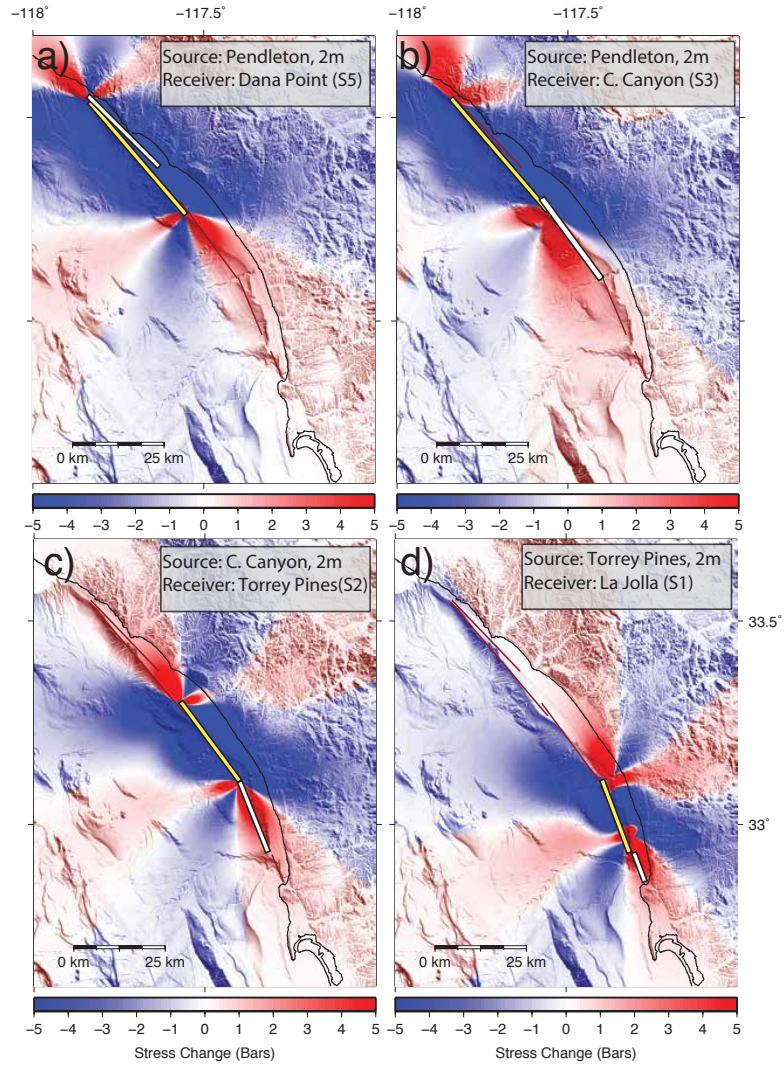


Figure 4.13: Rupture scenario III - Coulomb stress change from 2m of displacement starting on the Camp Pendleton source fault (yellow bar) and propagating south. Receiver segments marked by white bars. a) Stress change on the Dana Point receiver fault (S5) from the Camp Pendleton source fault (S4). The Dana Point strand is in the stress shadow. b) Stress change on the Carlsbad Canyon receiver fault (S3) from the Camp Pendleton source fault (S4). The Carlsbad Canyon fault is on the eastern edge of increased stress lobe. c) Stress change on Torrey Pines receiver fault (S2) from the Carlsbad Canyon source fault (S3). The Torrey Pines strand is in the center of the lobe of increased stress. d) Stress change on the La Jolla receiver fault (S1) from the Torrey Pines source fault (S2). The La Jolla strand is also in a region of increased stress change.

ture will continue through all three stepovers, in which case it is possible that the all offshore segments of the NIRC fault zone may rupture in a single event. The numerical modeling results; however, presented here suggest that the La Jolla/Torrey Pines stepover may act as an inhibitor to throughgoing rupture. Similar numerical methods have been employed in other regions, such as on the North Anatolian Fault in the August 1999 Izmit Earthquake to understand triggering of adjacent segments in a stepover (*Lettis et al.*, 2002). This study focused predominantly on the width of the stepover, and their results for the Izmit earthquake confirmed the hypothesis posed by *Wesnowsky* (2006). In the case of the NIRC, however, the coulomb stress tests performed imply that the dip and strike of adjacent segments may control whether rupture will propagate through the segment boundary in addition to the stepover width, as observed in Figure 4.10. A vertical La Jolla segment would impart a larger stress increase onto the Torrey Pines segment than the observed 67° SW dip on the La Jolla segment. The dipping La Jolla source fault (67° SW) is unlikely to promote through going rupture onto the Torrey Pines strand because of the pattern of increased Coulomb stress (Fig. 4.11a). Therefore northward propagation of rupture on the NIRC fault zone initiating on the La Jolla strand might terminate at the La Jolla/Torrey Pines stepover in effect limiting the potential magnitude of the earthquake. In the unlikely event that rupture does continues north onto the Torrey Pines strand, the Coulomb stress modeling suggests it increases the likelihood that all NIRC strands would rupture yielding a larger magnitude earthquake (Fig. 4.11).

The remaining two scenarios (e.g., southern propagation from the Camp Pendleton strand and propagation from the central Carlsbad Canyon strand) in this study propose that the possibility still exists for all offshore segments to rupture in one event (Figs. 4.12 and 4.13). The worst-case scenario stems from rupture initiated on the Carlsbad Canyon NIRC segment. As demonstrated by Figure 4.12, this scenario would significantly increase stress on all other segments, potentially triggering all the NIRC offshore segments. The final scenario presented here considers displacement on the Camp Pendleton segment of the NIRC fault zone. Here, stress is increased by a moderate to significant amount on all segments, bar the

Dana Point segment, which lies in its stress shadow. This scenario would account for rupture on 4 of the 5 segments (Fig. 4.13).

Figure 4.14 illustrates the segments assumed to rupture for each scenario. Green shading implies that the segment ruptures, and red shading implies that it does not. Figure 14a corresponds to scenario I, or the triggering implied by northward propagation with initiation on the La Jolla segment (Figure 4.11). Here, the La Jolla segment is the only offshore segment to rupture. Figure 4.14b corresponds to scenario II in which all segments rupture (initiation on the Carlsbad Canyon strand, Figure 4.12). Finally, Figure 4.14c illustrates the third scenario, for rupture initiation on the Camp Pendleton segment in which only four segments rupture in one event.

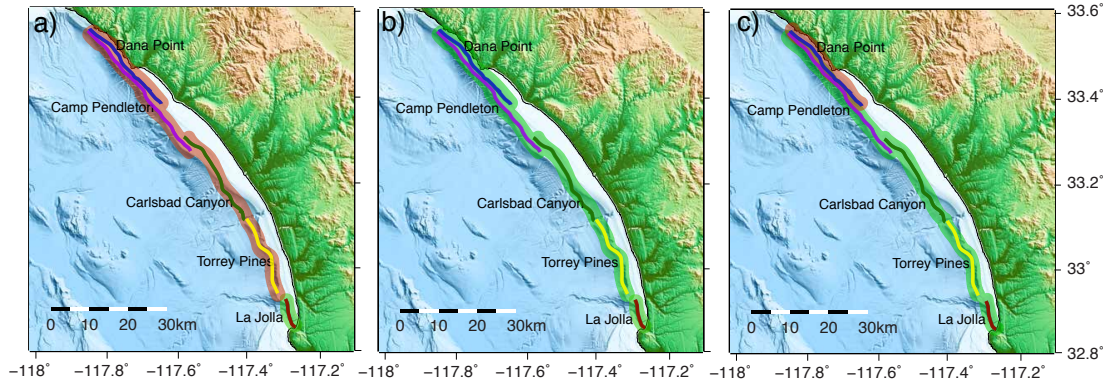


Figure 4.14: Examples of rupture scenarios based on modeling the Coulomb stress. Green indicates rupture on a segment, and red indicates no rupture on the segment. The segment colors are the same as in Figures 8 and 9. a) Corresponds to Figure 11, in which rupture is initiated on the La Jolla segment. It is unlikely that the other segments will rupture. b) Corresponding to Figure 12, this scenario depicts all segments rupturing if the event initiates on the Carlsbad Canyon segment. c) Scenario III corresponds to Figure 13, for which all segments rupture except the Dana Point strand, if the event is initiated on the Camp Pendleton strand.

Table 4.1 summarizes the potential magnitudes for these three scenarios. These were calculated by two methods, and are computed only for rupture on offshore segments. These values do not include onshore segments as these are not mapped in this study. The first method of computation employed the *Wells and Coppersmith* (1994) regression parameters from their Table 2A (*Wells and Cop-*

Table 4.1: Computed magnitudes for each scenario rupture presented here.

Rupture Scenario	Scenario I La Jolla Figure 4.11	Scenario II All Segments Figure 4.12	Scenario III 4 Segments Figure 4.13
Total Rupture Length	26 km	125km	83 km
Wells-Coppersmith	M_w 6.4 $\pm$ 0.13	M_w 7.5 $\pm$ 0.16	M_w 7.2 $\pm$ 0.16
Slip: 0.5 m μ : 20 GPa	M_w 6.3	M_w 6.7	M_w 6.6
Slip: 0.5 m μ : 45 GPa	M_w 6.5	M_w 7.0	M_w 6.9
Slip: 2m μ : 20 GPa	M_w 6.7	M_w 7.1	M_w 7.0
Slip: 2 m μ : 45 GPa	M_w 6.9	M_w 7.4	M_w 7.3

persmith, 1994), relating strike-slip subsurface rupture to earthquake magnitude. Subsurface rupture length was considered as opposed to surface rupture length for two reasons. The first is that the seismic data presented in this study constrain deformation at depth, and therefore this parameter was presumed to be a more appropriate measure of rupture length for this study. Second, Wells and Coppersmith mention that they found subsurface rupture length to be a more appropriate measure of magnitude because events often cause deformation at depth for a longer segment of fault than at the surface, and ground rupture is not always observed.

The second method of magnitude computation used seismic moment, and is shown in Table 4.1. Here, the fault area was computed with the total rupture length for each scenario (Table 4.1), and an approximate depth for the down-dip extent of rupture. In this region, the depth of microseismicity (assumed to be the brittle-ductile transition) is approximately 15km (*Astiz and Shearer*, 2000), so the depth used for the calculation of fault area was 13 km. Two values of shear modulus were used as end-members; 20 GPa, and 45GPa. These values were derived from the P and S wave velocities of a 1D profile on the shelf near Oceanside, from the Southern California Earthquake Center Community Velocity Model – Harvard (SCEC CVM-H) (*Shaw et al.*, 2015). Two values of slip were

also used as examples of a lower and upper bound: 0.5 m coseismic slip, and 2 meters coseismic slip. The upper bound was a result of the findings of *Lindvall and Rockwell* (1995) and *Rockwell* (2010), which stated that one location may have experienced up to 3 meters of coseismic slip in one event. The coulomb models were computed using 2 meters of slip as well.

The lowest potential magnitudes computed, M_w 6.3 – 6.9, were derived from Scenario I, with slip solely on the La Jolla segment, from Mt. Soledad. Scenario III provides an intermediate case, for which magnitudes could be expected at M_w 6.6 to 7.3. The largest potential event stems from Scenario 2, or slip on all segments – at M_w 6.7 – 7.5. The magnitudes derived from the Wells-Coppersmith regressions are higher than the first three seismic moment calculations, for Scenarios 2 and 3. The Uniform California Earthquake Rupture Forecast, version 3 (UCERF3) (*Field et al.*, 2014) seismic moment rate per year for the Rose Canyon fault is estimated at 2.49×10^{16} Nm/year and 2.00×10^{16} Nm/year for the offshore Newport Inglewood fault. Assuming the last earthquake for both these faults was 1650 ± 120 years ago, the resulting event on the Rose Canyon and Newport Inglewood faults after 500 years of moment accumulation would be M_w 6.66 and M_w 6.60, respectively. If both faults ruptured together faults, the accumulated seismic moment would result in an event of size M_w 6.83. This is less than predicted from the values in this study for rupture on all segments and slip magnitudes except for 0.5 m slip and a shear modulus of 20 GPa (near the surface).

The depth of the most recent episode of deformation varies along-strike in the NIRC fault system, which poses interesting questions regarding the nature of past earthquakes and their deformation characteristics. In the north, on the Dana Point and Camp Pendleton segments, the deformation does not reach the seafloor, but is shallower than many other areas along the NIRC fault zone. This could perhaps be from deformation associated with the 1933 Long Beach event. The deformation depth is deepest in the central region of the area of study, Carlsbad Canyon segment and southern portion of the Camp Pendleton segment (i.e., offshore San Onofre). One hypothesis to explain this observation is that this middle section may have ruptured at the same time as other sections or segments, how-

ever this region did not experience any surface rupture. Another hypothesis is that this section of the fault zone has been inactive for a longer period of time than the northern and southern regions, and thus could be a seismic gap. Coring the stratigraphic sequences that are offset is necessary to discern between these two hypotheses.

A final question that arises from these results refers to strain partitioning between strands. As noted, it appears that north of Las Pulgas or San Onofre, the NIRC fault zone is more fragmented as more strands are observed. Additionally, the slip rate at Newport Beach, approximately 0.5 to 1 mm/yr, is significantly lower than in the south by La Jolla, 1.5 – 2 mm/yr. It is noted by some (*Freeman et al.*, 1992) that the onshore northern region of the NIRC fault zone is characterized by splays and en echelon faulting, and that this may reduce the slip rate and complicate identification of active traces. This study could perhaps be observing the same phenomenon offshore. Though geodetic data is absent offshore, this too could be at least partially resolved through coring offshore.

4.5 Conclusions

Through the use of nested active-source seismic data, this study identified 5 main strands of the offshore NIRC fault zone, and three stepovers of approximate widths 2km (Torrey Pines popup), less than 0.5km (Carlsbad Canyon stepover), and 1.5km (San Onofre stepover); this study provides new insight into the geometry of the NIRC fault system. It improves the characterization of offshore stepovers, and provides rupture scenarios based on triggering across these stepovers due to static stress changes. Through these investigations, it has determined that fault dip and strike at a stepover are important parameters in determining if rupture may propagate through the segment boundary. Such an approach should be employed when considering stepovers and rupture propagation in addition to stepover width. Finally, it has revealed that based on these new mappings and insights, the NIRC fault zone could, depending on rupture characteristics, produce an earthquake of up to magnitude M_w 7.4 or 7.5. These results argue that further study should be

performed to improve the current understanding of hazard and potential ground shaking posed to the urban coastal areas from Tijuana to Los Angeles from the NIRC fault zone, as well as from other faults in the ICB. Offshore structures may play a more significant role in regional hazard than previously thought, and should be considered an active player in seismic risk for Southern California.

4.6 Acknowledgements

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Chapter 5

Conclusions

The overarching theme of this dissertation has been to use marine active-source seismic imaging as a tool to characterize the architecture of active tectonic structures and systems in Southern California, for both geologic purposes of understanding local tectonic evolution and geomorphology, and for improving current estimates of regional seismic risk.

Chapter 2 focused on the geologic evolution of the Salton pull-apart basin. It constrained the shallow crustal velocity structure of the Salton Sea and surrounding area in the Salton Trough, and placed constraints on the time evolution of deformation in the Imperial-San Andreas pull-apart system. Slip on the southernmost SSAF diminished, and was replaced by northward growth of slip in the Brawley Fault Zone. This subsequently prompted further development of local extensional basins such as the Salton and Mesquite pull-apart basins, imprinted onto the regional extension in the Salton Trough. The reflection and refraction data presented here provide insight into the evolution of the segment boundaries of this system, as well as the strain partitioning between the observed fault zones. It also offers new evidence and constraints applicable to earthquake triggering scenarios and the communication of stress between faults. It suggests the presence of a previously unknown fault structure in the Salton Sea (albeit not or poorly imaged with these data) striking approximately parallel to the SSAF.

The focus of Chapter 3 was to further investigate this structure west of the SSAF, the Salton Trough Fault (STF). It employed active-source seismic refraction

and reflection data in the Salton Sea, LiDAR data, and geologic observations to constrain the nature of the STF. It imaged the reflectors and velocity structure of the lake sediments and basement, and provided strong evidence for a transtensional STF. As a previously unidentified structure, the existence of this fault holds significant implications for community fault models and earthquake rupture forecasts such as the Southern California Earthquake Center (SCEC) Community Fault Model (CFM) (*Plesch et al.*, 2007) and the Unified California Earthquake Rupture Forecast 3 (UCERF3) (*Field et al.*, 2014). It may further impact models of stress communication between local faults in the pull-apart basin, and could alter models of ground motion for scenario ruptures (*Olsen et al.*, 2008), as well as affect regional hazard maps.

Finally, Chapter 4 employed nested marine active-source seismic data with unprecedented regional data density and resolution to improve the characterization of the offshore NIRC architecture and segmentation. Based on the seismic data, five main segments or strands of the offshore NIRC were identified, and three main segment boundaries or stepovers. With this new information, it offered several rupture scenarios on the fault system based on static stress triggering across segment boundaries. These investigations of static stress triggering lead to the observation that strike and dip of fault strands at a stepover or segment boundary is an important component in communication of stress, and as such, future assessments of throughgoing rupture at segment boundaries should combine an observational and quantitative approach. Lastly, the results of this study showed that the offshore NIRC is capable of producing up to a Mw 7.4 or 7.5 earthquake, depending on the rupture characteristics. These results suggest an equal to greater hazard than previously imagined, since the magnitude is greater than the former maximum potential event magnitude predicted for these two fault systems (*Field et al.*, 2014).

The results presented in these chapters identify the required steps forward, and incite new scientific and societal questions. The obvious study that follows from the conclusions of Chapters 2 and 3 is to model communication of stress between all faults observed in the Salton pull-apart system, both dynamically and

statically. Because the style of deformation of the STF is transtensional and perhaps slightly westward-dipping, it is important to understand the ground shaking that may result from rupture on this fault due to hanging wall effects and radiation patterns. Further ground motion simulation suites should be conducted to understand the effects that may result from the interplay of rupture between these faults. Additionally, marine active-source seismic techniques could be employed in the irrigation canals of the Imperial Valley to further understand the faulting of the associated Imperial fault system, and place constraints on the timing of deformation of the splays of this system. These results could also play an important role in our understanding of the complicated dynamics of the Imperial-San Andreas system.

The UCERF3 model currently describes the onshore and offshore Newport-Inglewood and Rose Canyon systems as separate entities. Chapter 4 shows that there is no clear evidence to classify them as separate and distinct faults. Further work should be conducted to understand the dynamics of the onshore segments, and make predictions of potential magnitude and rupture scenarios based on both onshore and offshore fault mappings. Studies of dynamic triggering could be conducted on these segments to complement the static triggering results. Ground motion simulations also should be investigated for the NIRC fault system to improve the current predictions of ground shaking in Los Angeles, Orange, and San Diego counties, as well as in Tijuana and northern Baja California.

The discussion now comes full circle, and returns to the broader purpose of this work examined in the thesis introduction: How can we better prepare for large earthquakes in Southern California? The main contributions of this thesis have been to improve characterization of fault structures in southern California, to identify new fault structures, and understand better the implications of segmentation in these fault systems. It has provided critical constraints on parameters for regional seismic risk estimation, and here, has suggested steps to take in this assessment. In conclusion, these results not only raise interesting questions about future approaches to studying fault segmentation and its control on margin architecture, it also provide a stepping stone to regional hazard estimation, such

as updating community fault models and rupture predictions (*Plesch et al.*, 2007; *Field et al.*, 2014), or improving regional structural codes.

Chapter 6

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