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**3D Fault Geometry and Basin Evolution in the Northern
Continental Borderland Offshore Southern California**

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A Thesis Submitted to the Department of Physics and Geology

California State University Bakersfield

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**3D Fault Geometry and Basin Evolution in the Northern
Continental Borderland Offshore Southern California**

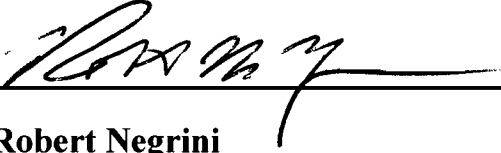
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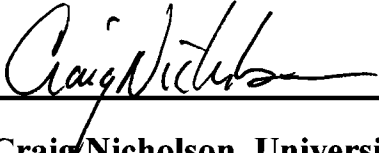
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Dedication

I would not have been able to complete this work without the support and nagging of family, friends and colleagues. A special thank you goes to my mom, Dorene and my sister Corinne, for always being there when I needed them. A thank you to my best friend and colleague Jared Brinton, who constantly encourages me to be the best geologist I can be. I also would not have been able to complete this work without the support of my colleagues at Berry Petroleum Company: Edward Besenfelder, Bassam Alameddine, Craig Zubris, Carol Beahm, Sneha Patel, Jennifer James, Eloy Villanueva, Ben Mendes, Zac Hale and Tom Cruise.

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I also would like to thank Marc Kamerling and Ron Heck for providing valuable data and knowledge, the California Well Sample Repository for providing well and core data, Western GeoCo and other companies for releasing various data sets, and the help of Jon Childs and Ray Sliter (USGS) for providing access to MCS data through the NAMSS website. NSF-Tectonics funded the bulk of this research. Seismic Micro-Technology donated the interactive, 3D seismic data interpretation and visualization software used in this project.

Abstract

Multichannel seismic (MCS) reflection data, bathymetry and offshore well data are used to map fault surfaces and stratigraphic reference horizons in the northern Continental Borderland offshore of southern California, an area that experienced large-scale oblique crustal extension and translation associated with the initiation and development of the Pacific-North American plate boundary. The 3D surfaces of structure and stratigraphy can thus be used to better understand and evaluate regional patterns of uplift, subsidence, fault interaction and other aspects of plate boundary deformation. Mapping in Santa Cruz basin, and on Santa Rosa and Santa Cruz-Catalina ridges reveals distinct patterns of faulting, folding and basin subsidence. Major findings include: (a) significant vertical motions, up to 3-4 km since early Miocene time, estimated from the deformation of an early Miocene unconformity that likely represents a paleo-horizontal surface eroded near sea level; (b) a characterization of the complex 3D geometry and pinch-out of the eastern edge of the northern forearc basin rocks of the Nicolas terrane which has implications for Borderland basin development, plate reconstructions, and vertical motions associated with oblique rifting; (c) recognition that the East Santa Cruz Basin fault, previously thought to be a predominantly high-angle, large displacement right-slip fault representing the eastern edge of the Nicolas terrane, is in fact a series of reactivated right-stepping, NE-dipping reverse-separation faults; (d) discovery that NW-striking faults associated with Santa Cruz-Catalina Ridge bend westward into and contribute to the southern frontal fault system of the Northern Channel Islands anticlinorium; and (e) recognition that both Santa Cruz-Catalina Ridge and Santa Rosa Ridge are Cenozoic basins inverted by post-Miocene compressional folding.

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Introduction

The California Continental Borderland located offshore southern California (Figure 1) occupies an advantageous position along the continental margin that results in a well preserved record of plate boundary deformation including subduction, transform initiation, oblique rifting, and transpression. The Borderland is bounded on the north by the rotated western Transverse Ranges province, to the east by the Peninsular Ranges and to the west by the Patton Escarpment (Figure 1). It is divided into two major sections: the Inner and Outer Borderland. The Outer Borderland includes lithotectonic terranes that represent an accretionary wedge complex and a forearc basin that formed during subduction of the Farallon plate from the Triassic to the Mid Cenozoic (Jones *et al.*, 1976; Crouch, 1979; Howell and Vedder, 1981). Uplift and extension that began in early Miocene time separated these older terranes from their associated magmatic arc (the Peninsular Range batholith) (Crouch and Suppe, 1993). This extension exhumed the intervening and tectonically denuded region that comprises the Inner Borderland (Figure 1) (Crouch and Suppe, 1993). This large-scale extension resulted in the Continental Borderland occupying a zone nearly twice as wide as anywhere else along the North American western margin and is similar in extent to the amount of crustal extension in the Basin and Range province (Wernicke, 1992; Crouch and Suppe, 1993). In contrast, most of the Outer Borderland is generally interpreted to not have experienced large-scale deformation of the upper crust (Bohannon and Geist, 1998; ten Brink *et al.*, 2000; Crouch and Suppe, 1993; Nicholson *et al.*, 1994; Miller, 2002).

The Borderland possesses a well-preserved, long tectonic record of plate boundary evolution. It has been inferred as the locus of Pacific-North American plate motion from about 19 Ma to 6 Ma (Nicholson *et al.*, 1994) and is accommodating potentially as much as

twenty percent of current plate motion between the Pacific and North American plates (Beavan *et al.*, 2002, Dixon *et al.*, 2000). During much of this time, the Borderland has been mostly an area of deposition, rather than erosion. Therefore, a nearly continuous syntectonic sedimentary record is present to preserve this tectonic history.

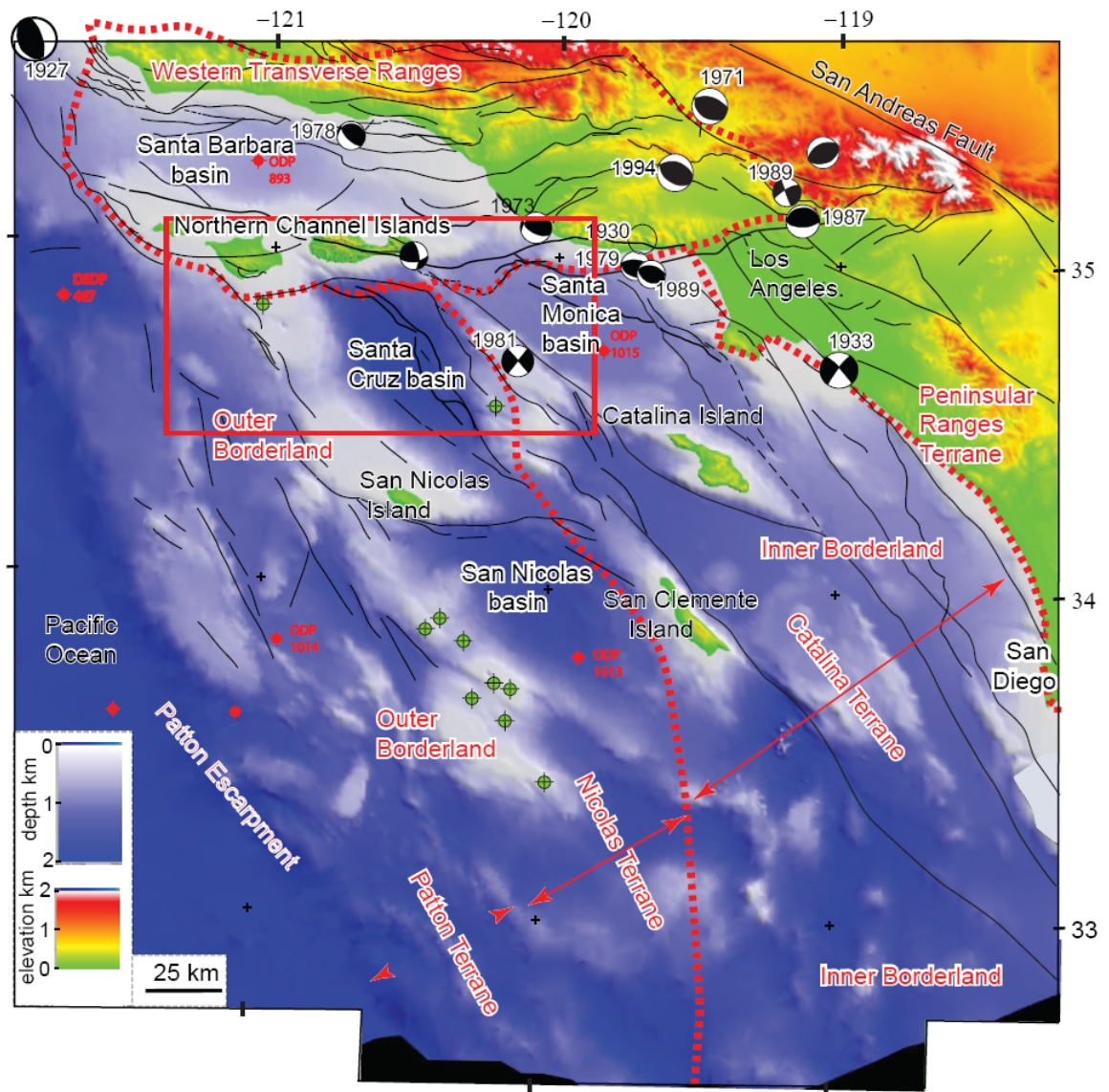


Figure 1: Map of the California Continental Borderland showing bathymetry. Locations of major tectonic provinces (e.g., Western Transverse Ranges, Peninsular Ranges, Inner Borderland and Outer Borderland) are shown and separated by red-dashed lines. Approximate widths of offshore tectono-stratigraphic terranes (Patton, Nicolas and Catalina) are shown with double-headed arrows.

The offshore locality of the Borderland allowed for the use of marine geophysical data to image and map structure and stratigraphy in 2D and 3D. Several previous studies of the Borderland relied primarily on a few regional profiles of seismic reflection and gravity data (Bohannon and Geist, 1998; ten Brink *et al.*, 2000; Miller, 2002). For this study, a combination of different geologic and geophysical datasets were used to provide more comprehensive 3D coverage, including newly released grids of high-quality industry 2D multichannel seismic (MCS) reflection data, stratigraphic data from two wells (Chevron P-0245 and Mobil P-0289), results from dense seafloor geologic samples on Santa Rosa Ridge (R. Heck, written communication, 1994), scattered core holes, and multibeam bathymetry (Figure 2).

The expanded interpretation allowed by this diverse data set can be used as analogues for onshore structures that may be less accessible. In addition, the northern edge of the Borderland is a transitional region between the predominantly NW-SE striking features of the Inner and Outer Borderland and the E-W striking features of the rotated western Transverse Ranges province. Thus, the Borderland provides an opportunity to study the interactions of different fault systems as they approach one another.

The Borderland consists of a series of shallow ridges separating deep sedimentary basins (Figure 1). This project focused on one of these deep basins (Santa Cruz basin) and the two adjacent ridges (Santa Cruz-Catalina Island Ridge and Santa Rosa Ridge). Utilizing the integrated data set developed for this area, digital stratigraphic reference horizons and 3D fault surfaces were developed to define active fault and fold geometry, and the regional pattern of uplift, subsidence, and basin development. These results are used to test and evaluate various tectonic models (Crouch and Suppe, 1993; Nicholson *et al.*, 1994;

Bohannon and Geist, 1998; ten Brink *et al.*, 2000; Miller, 2002) for Borderland evolution including the expected basin structure, the predicted geometry of basin-bounding faults, and the influence of inherited tectonic structures and the previous tectonic history on subsequent deformation.

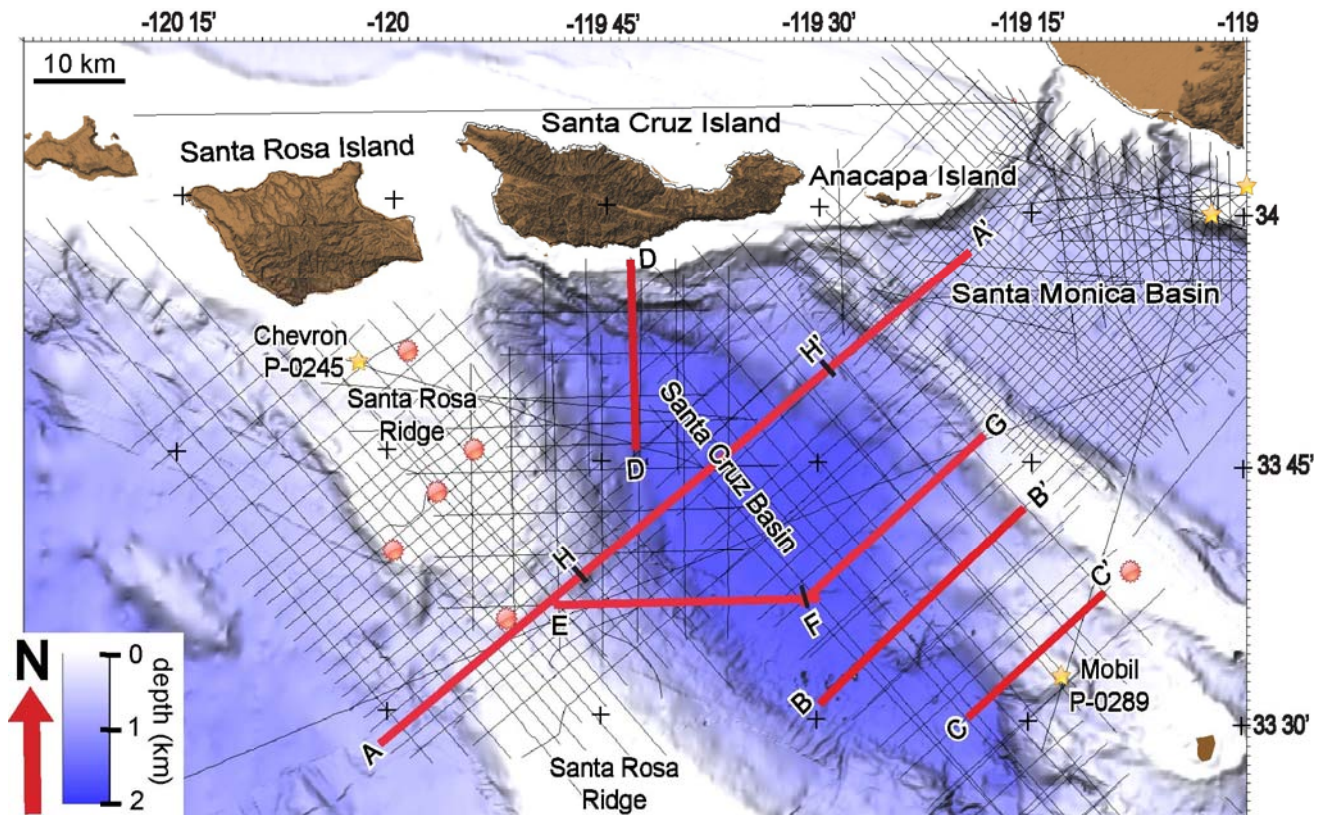


Figure 2: Basemap of study area showing shaded bathymetry and grids of 2D multichannel seismic (MCS) reflection lines. These MCS surveys typically consist of 240-channel, 60-fold data recorded to 6.0 s TWTT. Seismic lines displayed on subsequent figures are shown in red. Locations of offshore wells are shown with yellow stars and coreholes by pink circles.

Regional geology and Previous work

Tectonic Provinces of the Continental Borderland

The accretionary wedge and forearc basin terranes of the Outer Borderland are tectonostratigraphic terranes that developed subparallel to the Patton Escarpment, the remnant of the convergent margin trench (Jones *et al.*, 1976; Crouch and Suppe, 1993) (Figure 1). The outer accretionary wedge complex is the Patton Terrane. Its basement is

composed of the Franciscan Assemblage (Jones *et al.*, 1976) and constitutes the westernmost Outer Borderland (Figure 1, 3). The Nicolas terrane is inboard of the Patton terrane, contains pre-Miocene forearc basin rocks (Great Valley Sequence equivalent) and constitutes the eastern Outer Borderland (Figure 1, 3). East of the Inner Borderland, the Peninsular Ranges correspond to the magmatic arc associated with the earlier phase of Farallon plate subduction.

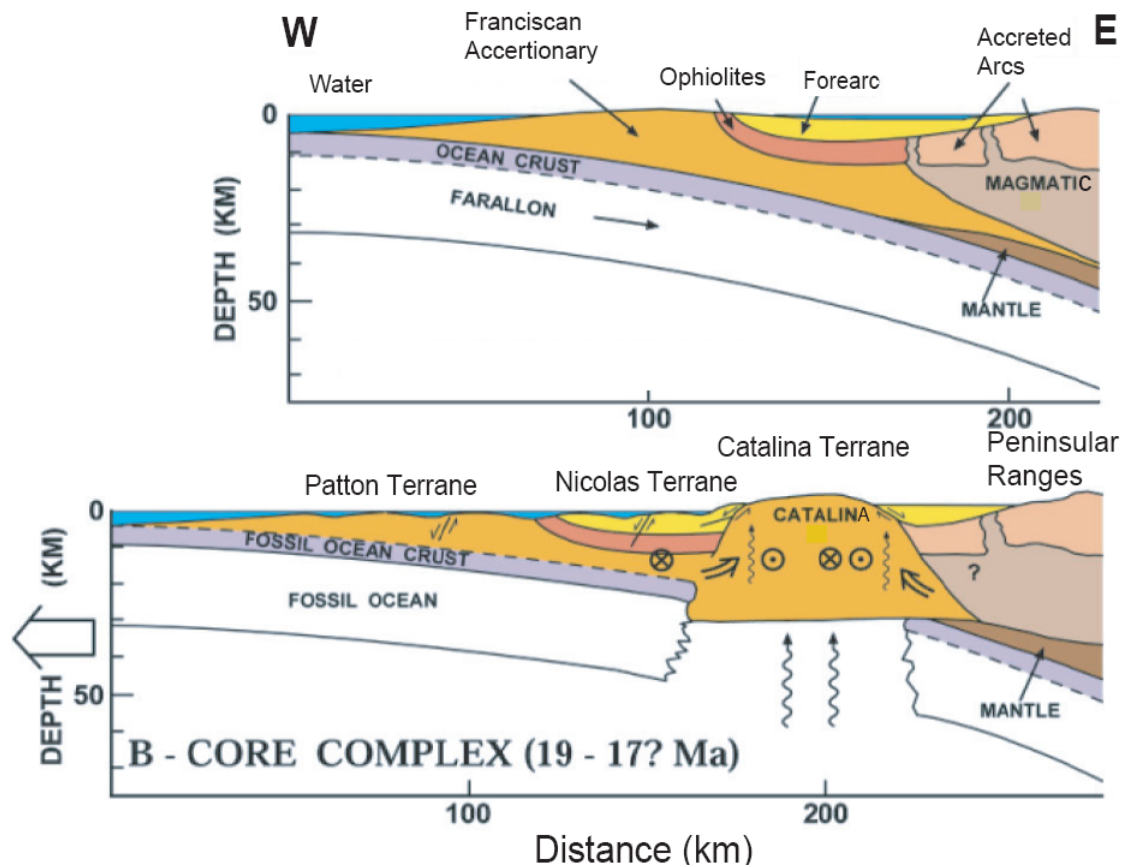


Figure 3: Tectonic model for Borderland evolution and crustal structure [ten Brink *et al.*, 2000]. (A) Development of accretionary wedge (Patton terrane) and forearc basin (Nicolas terrane) of the Outer Borderland during Farallon plate subduction. (B) Development of Inner Borderland (Catalina terrane) as mega-metamorphic core complex above a slab gap during early-Miocene oblique rifting. The Nicolas terrane, which includes the sedimentary rocks of the forearc basin, rifted away from the Peninsular Ranges, allowing the tectonic exhumation of the Catalina terrane in between.

The Outer Borderland terranes are separated from the magmatic arc by the highly extended Catalina terrane that makes up the Inner Borderland (Figure 1, 3). The Catalina

terrane formed in conjunction with the rifting and rotation of the western Transverse Ranges province and the Outer Borderland away from the North American plate (Crouch and Suppe, 1993; Nicholson *et al.*, 1994). Its basement consists of mostly Franciscan Complex equivalent rocks metamorphosed into higher grade Catalina Schist. This basement is overlain by Miocene and younger sedimentary rocks (Crouch and Suppe, 1993). The boundary between the Inner (Catalina terrane) and Outer (Nicolas and Patton terrane) Borderland has been previously considered to be the East Santa Cruz Basin (ESCB) fault system based upon geological (Crouch and Suppe, 1993; Bohannon and Geist, 1998) and both gravity and magnetic data (ten Brink *et al.*, 2000; Miller, 2002). The geometry of the ESCB fault system has been interpreted to be either a near-vertical right-lateral strike-slip fault (Howell and Vedder, 1981), or a west-dipping high-angle fault with both a large amount of right slip and normal separation (Bohannon and Geist, 1998; ten Brink *et al.*, 2000).

Tectonic Evolution of the Borderland

From the Triassic to the Oligocene, the Farallon plate subducted beneath the North American plate. At about ~26-28 Ma, the Farallon-Pacific spreading ridge first reached this subduction zone (Atwater and Stock, 1998). This began the cessation of subduction along the Farallon-North American boundary and the establishment of a Pacific-North American transform plate boundary. During the ending phase of subduction, the Farallon plate began to fragment into various pieces (Figure 4), including the Monterey and Arguello microplates (Lonsdale, 1991).

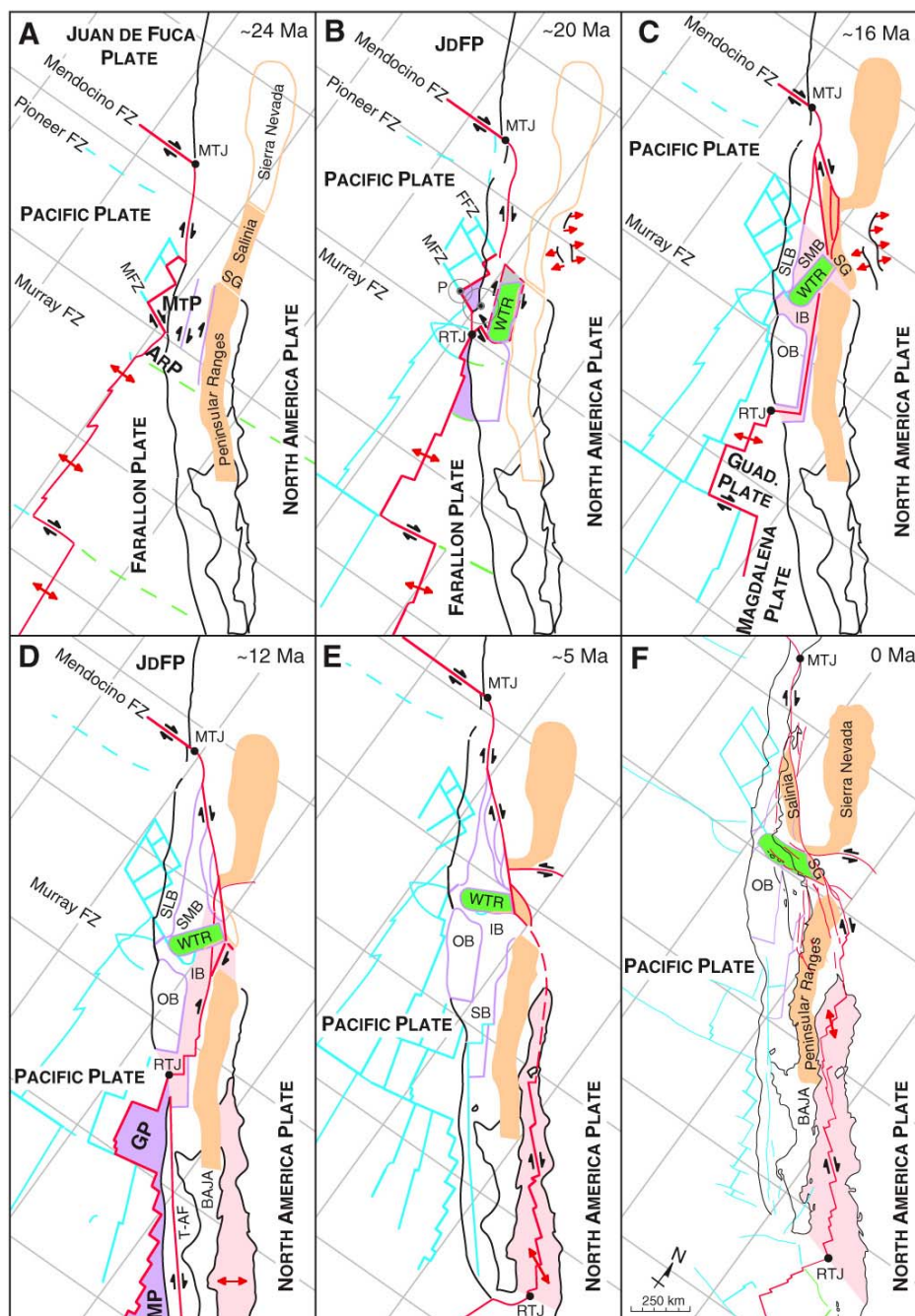


Figure 4: A simple tectonic model of the evolution of the Pacific-North American plate boundary that includes the Inner and Outer Borderland (IB, OB) and rotation of the western Transverse Ranges (WTR) province (from Nicholson et al, 1994). The model assumes a constant rate and direction of Pacific plate motion and constant rate of western Transverse Ranges rotation. As each partially subducted microplate is captured by the Pacific plate (Monterey, ~19 Ma; Arguello, ~17.5 Ma; Guadalupe and Magdalena, ~12 Ma), this results in a transfer of part of the over-riding North American upper plate to the Pacific plate. The fine gray lines provide a reference grid fixed to North America. ArP-Arguello plate; GP-Guadalupe plate; MtP-Monterey plate; SG-San Gabriel block; JdFP-Juan de Fuca plate; SLB-San Lucia Bank; SMB-Santa Maria basin; SB-southern Borderland; T-AF-Tosco-Arbrejos fault; MP-Magdalena plate. Red areas are regions of transtension; Purple areas are captured or soon to be captured microplates.

In Nicholson, *et al.* (1994), the Monterey (MtP) and Arguello (ArP) microplates are modeled to have eventually coupled to the Pacific plate, causing their plate motion vectors to rotate and the Pacific-North American boundary to lengthen as each partially subducted microplate was captured. Spreading between the Monterey and Pacific plates ended at about 19 Ma, allowing this microplate to begin to move with Pacific plate motion (Nicholson *et al.*, 1994). As a result, parts of the overriding continental crust also took on components of Pacific plate motion and began to move along the plate boundary. One of these overriding pieces, the western Transverse Ranges province, did not simply translate with Pacific plate motion, but instead rifted and rotated clockwise by more than 90° (Kamerling and Luyendyk, 1985; Luyendyk, 1991), in part because it was believed to be buttressed to the north by a left step in the plate boundary geometry (Figure 4) (Nicholson *et al.*, 1994). This rotation and rifting was associated with extreme continental oblique extension that helped form the northern Inner Continental Borderland (Kamerling and Luyendyk, 1985; Legg, 1992; Crouch and Suppe, 1993; Nicholson *et al.*, 1994). ten Brink *et al.* (2000) proposed that this extension was further enhanced by the opening of a slab gap beneath the Inner Borderland that developed as the captured microplate pulled away from the down-going slab, a process that may have helped exhume the Franciscan/Catalina Schist basement.

The formation of the southern Inner Borderland is related to the rifting and oblique translation of the Outer Borderland (Kamerling and Luyendyk, 1985; Legg, 1992; Crouch and Suppe, 1993; Nicholson *et al.*, 1994). The Arguello-Pacific spreading center initially began to subduct beneath the North America at about 22 Ma and continued to subduct beneath what is now part of the Outer Borderland until about 17.5 Ma (Lonsdale, 1991), at which time the underlying Arguello microplate was either captured by the Pacific plate or

was fully subducted beneath the North American plate. This ridge subduction caused the triple junction formed by the Pacific, North American and northern remnant of the Farallon plate to rapidly migrate 300 km to the south (Lonsdale, 1991) and allowed another piece of the overriding North American plate to be subject to Pacific plate motion at its base. The net result was that this piece, which became the Outer Borderland block, also began to rift and separate from North America (Figure 4). It did not rotate like the western Transverse Ranges province because everything north of the Outer Borderland block was already moving northwestward with some component of Pacific plate motion and there was no buttress to pin the northern edge of this block (Nicholson *et al.*, 1994). The inferred delay between the onset of Outer Borderland rifting (~17.5 Ma) and the rifting associated with the capture of the Monterey microplate (~19 Ma) led to a significant break in the continental slope (Nicholson *et al.*, 1994).

At about 12 Ma, spreading ceased between the Pacific plate and the Guadalupe and Magdalena microplates located farther south (Lonsdale, 1991), allowing the Guadalupe and Magdalena microplates to be captured by the Pacific plate and to begin moving with Pacific plate motion (Figure 4). The capture of these microplates initiated the transfer of Pacific plate motion farther east. Finally, an inferred change in plate boundary geometry (Nicholson *et al.*, 1994) and plate motion vector (Wilson *et al.*, 2005) at about 6 Ma initiated the current transpressional regime within the offshore Continental Borderland. This latter deformation in turn reactivated, overprinted and inverted several of the extensional features associated with the earlier development of the rifted and rotated western Transverse Ranges province and the Outer and Inner Borderland (Legg, 1991; Crouch and Suppe, 1993).

Previous Work

The well-preserved tectonic history of the Borderland provides an opportunity to study the effects of several different tectonic processes that occurred with the evolution of the present plate boundary. The subduction of young, hot oceanic plates and ridges, the coupling of microplates to overlying continental crust and crustal rotations all contributed to the continental rifting and crustal exhumation that occurred in the Inner Borderland. Crouch and Suppe (1993) used a combination of geophysical interpretations and existing geological data as evidence for a metamorphic core-complex-like extension occurring in the wake of the rotating western Transverse Ranges province and translating Outer Borderland, causing the extension and exhumation of lower crustal materials in the Inner Borderland. They estimated the total amount of oblique crustal extension in the Inner Borderland at over 200 km. During this extension, a majority of displacement was inferred to be absorbed by bounding faults to the west, including the East Santa Cruz Basin fault system (Crouch and Suppe, 1993). Features associated with this model of exhumation include metamorphic core complex structures, large-scale detachment faults, voluminous Miocene age volcanic rocks, and fragments of Great Valley Sequence within the extended Inner Borderland. Utilizing well data, seismic reflection and seismic refraction data, Bohannon and Geist (1998) modeled upper crustal structure of the Inner and Outer Borderland with only minor deformation within the Nicolas Terrane as it translated passively to the northwest above deeper structures. In their model, the boundary between the Nicolas and Catalina terranes, or the boundary between the Inner and Outer Borderland, was also the East Santa Cruz Basin fault, which they interpreted to be a west-dipping fault with inferred normal separation.

ten Brink *et al.* (2000) focused on the deeper structure and crustal velocities of the Inner Borderland using a combination of wide-angle seismic reflection and refraction data, MCS reflection data, and gravity data along two regional crossing lines. ten Brink *et al.* (2000) found that the crust of the Inner Borderland was significantly thinner than comparable continental margin crust in Northern California. The Inner Borderland also lacked evidence for an underplated oceanic layer, suggesting that lower crustal exhumation occurred above a slab gap or slab window. Miller (2002) also used 2D regional seismic reflection lines and gravity data to help define crustal structure of the Northern Borderland. Miller (2002) compared crustal thickness between Northern California to that of the Outer Borderland, finding that the crust of the accretionary complex (Patton terrane) and forearc basin (Nicolas terrane) is about 10 km thinner. Miller (2002) proposed that this thinning of crust was due to the flow of lower crustal material from under the Outer Borderland to the Catalina terrane as the Inner Borderland metamorphic core complex was being exhumed. The gravity models used by Miller (2002) also imply the existence of a high-density layer beneath the Santa Cruz basin, which could possibly be ophiolite.

Data and Methods

Grids of high quality, deep-penetration industry MCS data (Figure 2), available from the USGS National Archive of Marine Seismic Surveys website (<http://walrus.wr.usgs.gov/NAMSS>) formed the primary basis for the mapping effort. The data are typically 240-channel, 60-fold, post-stack migrated time sections recorded to 6.0 seconds two-way travel time (TWTT). These MCS data were integrated together with well and corehole data, seafloor geology maps, and multibeam bathymetry. The well and corehole data, which included data from two industry wells (Chevron P-0245 and Mobil P-0289),

were obtained from the California Well Sample Repository on the California State University Bakersfield campus and provided important subsurface age and lithologic control. An unpublished seafloor geology map (R. Heck, written communication, 1994) with paleontology from numerous bottom samples was also used. In addition, a detailed bathymetry map was assembled by combining multibeam and point data bathymetry using datasets available from NOAA and USGS websites.

The digital MCS data were incorporated into a commercial interactive 3D visualization, analysis and modeling program (The Kingdom Suite™ from Seismic Micro-Technology) and integrated with the well and corehole data for 2D interpretation on individual seismic lines and for later 3D mapping. Multibeam bathymetric data were used to check the accuracy of the MCS navigation data. Seafloor geology helped confirm the interpretation of various seismic stratigraphic units traced to seafloor outcrop.

Reflective character, lateral continuity, seismic sequence stratigraphy and lithology from well and sea floor data determined the selection of various stratigraphic reference horizons (Figure 5). A high-amplitude reflection along the bottom of Santa Cruz Basin characterizes the oldest and deepest horizon picked, and is interpreted to be top igneous or metamorphic basement. The other interpreted horizons include a regional early-Miocene unconformity, a near-top-Miocene horizon, a conformable Pliocene horizon and a conformable Quaternary horizon (Figure 5).

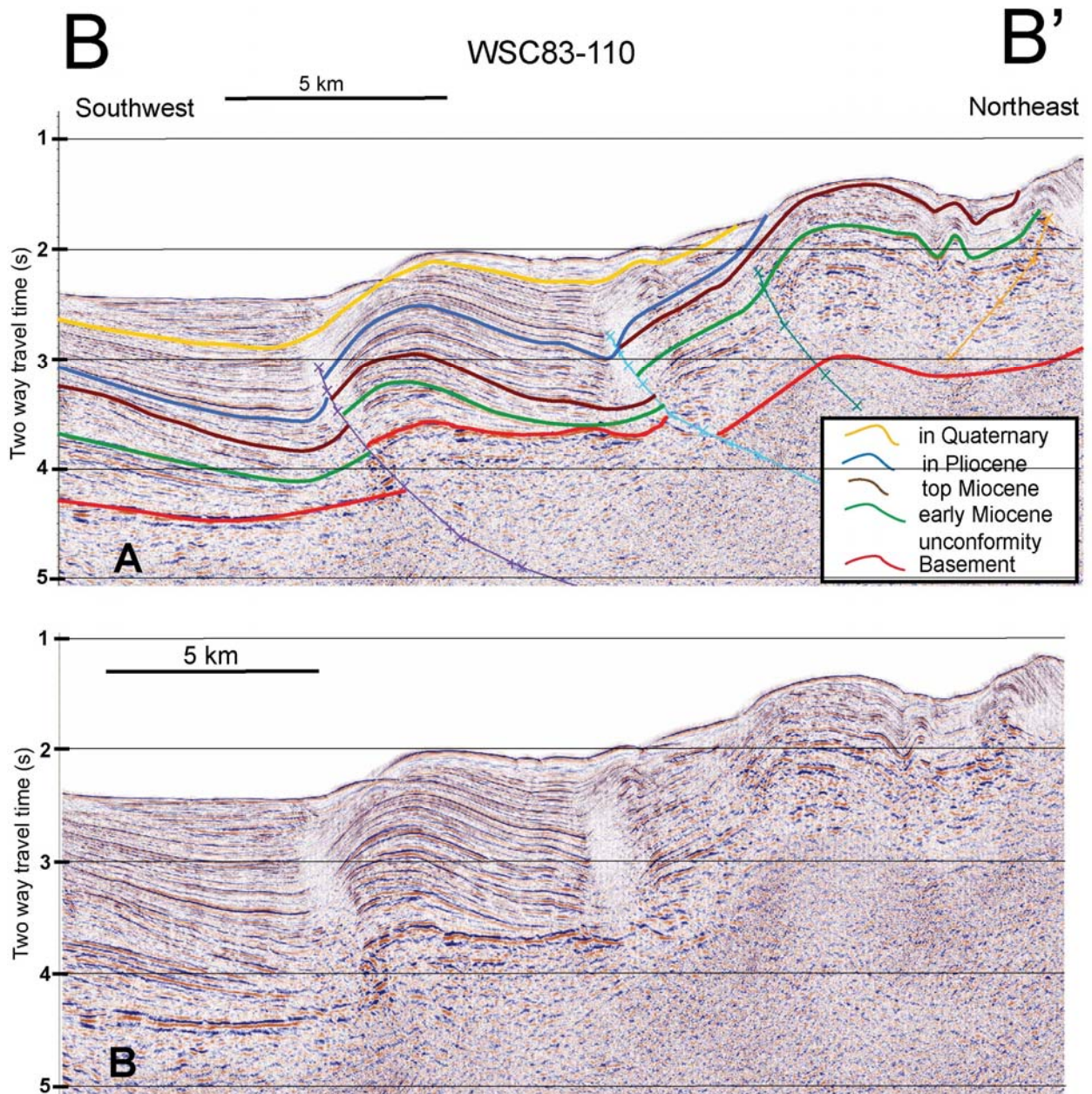


Figure 5: (A) Time migrated MCS line WSC83-110, located on Figure 2, looking northwest across active strands the East Santa Cruz Basin fault system with interpreted horizons and (B) WSC83-110 without interpretation.

The age of the regional early-Miocene unconformity was determined from core and bottom samples on Santa Rosa Ridge. This unconformity appears to correlate with the top of a basalt layer, also of early Miocene age, in the Mobil well on Santa Cruz-Catalina Island Ridge. The unconformity overlies the older, Cretaceous-Paleogene forearc basin rocks and is

overlain by middle and late Miocene sedimentary rocks. The regional nature of this unconformity, the large thickness of rocks eroded by it, and the conformable deposition of later sediments suggest that it was a near sea level, paleo-horizontal surface at the time of its formation. This horizon thus becomes a useful reference datum to evaluate subsequent vertical motions and the pattern of crustal deformation.

Interpretations of various stratigraphic reference time horizons were exported to Surface III, a program developed by the Kansas Geological Survey (<http://www.kgs.ku.edu/Tis/surf3/>) for creating gridded 3D surfaces. Projection of slopes was the gridding method used. Projection of slopes is a two-step gridding process. First, a local slope is calculated at each individual control point from the original data set, with closer points weighted more than distant ones using a fourth-order polynomial. These individual slopes are then projected onto the desired grid node location and averaged for the best fit (Davis, 1987). Terminations of sedimentary reflections, vertical separation of horizons based on loop tying, and fault plane reflections were used to identify and map active 3D fault surfaces. Distribution of post-Miocene sedimentary rocks and potentially active folding above interpreted faults was then taken as evidence for a component of reverse slip.

Gridded 3D surfaces were converted from two-way travel time (TWTT) to depth using a linear velocity equation for the Plio-Quaternary modern basin fill, and constant interval velocities in layers for the older rocks (Figure 6). The linear velocity equation used is (Tolmachoff, 1993):

$$Depth = \left(\frac{Vo}{0.6} \right) \times e^{\left[\left(\frac{0.6T}{2} \right)^{-1} \right]}$$

where V_o is the velocity at the seafloor (1500 m/s) and T is TWTT. The constant used in the equation (0.6) was obtained from empirical observations in adjacent basins (Marc Kamerling, pers. comm., 2007). The isochore maps of the sedimentary horizons were then added to the seafloor depth to produce horizons with respect to depth below sea level.

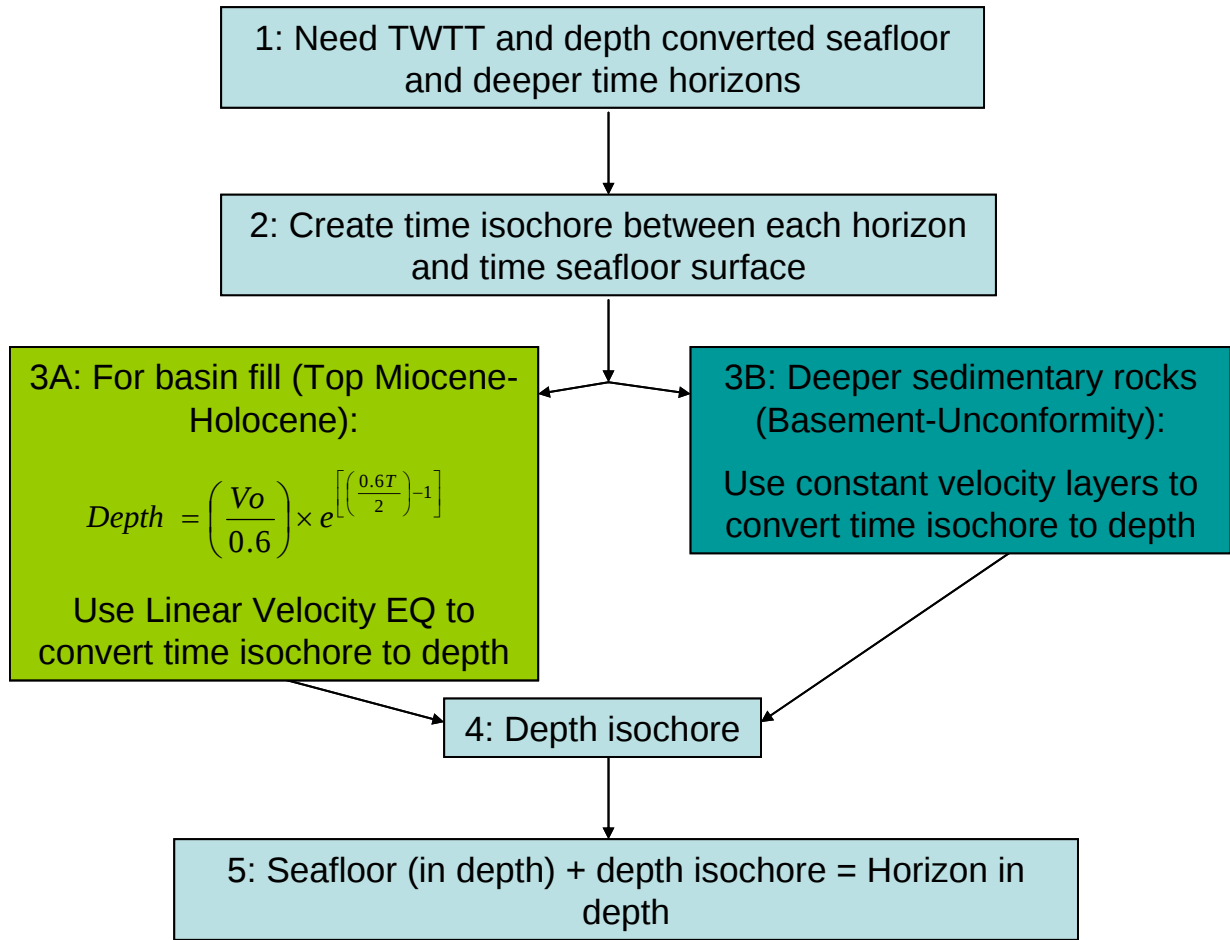


Figure 6: Flowchart outlining two different methods used to convert gridded 3D surfaces from TWTT to depth. (1) Seafloor bathymetry was converted to TWTT using a constant velocity (1490 m/s). (2) Isochore maps in TWTT were created by subtracting each subsequently deeper respective time horizon from the TWTT grid of the seafloor. (3A) Basin fill sediments (Top Miocene to Holocene) were depth converted using the linear velocity equation. (3B) For deeper sedimentary rocks (basement and early Miocene age unconformity), a constant averaged velocity was used for each interval in place of conversion by the linear velocity equation. (4) The result of each method was a depth converted isochore map of each horizon (5) The relative depth isochore maps of the sedimentary horizons were then added to the depth converted seafloor bathymetry to produce horizons with respect to depth below sea level.

Constant averaged velocities were used for two intervals of sedimentary rocks below the Top Miocene horizon. Seismic velocities measured in wells on both Santa Rosa and

Santa Cruz-Catalina Ridges are relatively high (about 3 km/s for middle and late Miocene and about 4 km/s for Paleogene rocks), implying that these sedimentary rocks were once deeply buried and are now more compacted and lithified. This observation made it possible to use these same velocities for these older sedimentary rocks where they are still buried more deeply in the deeper basin.

Observations and Results

Vertical Motions in the Outer Borderland

The changing thickness and distribution of sedimentary rocks and the current depth and geometry of the early-Miocene unconformity suggests the presence of significant vertical motions associated with the evolution of this portion of the Pacific-North American plate boundary. The early-Miocene unconformity, which is interpreted to represent a paleo-horizontal, near paleo-sea level surface, now resides at a depth of ~4 km below sea level in the eastern part of Santa Cruz Basin and about 500 m below the top of Santa Rosa and Santa Cruz-Catalina Ridge (Figure 7). This implies that there has been a significant history of regional uplift to generate the unconformity and subsequent subsidence to generate its current configuration and depth distribution within the Borderland (Figure 7, 8). The elevated and folded geometry of the unconformity and younger pre-Pliocene conformable sediments, together with the thicker, pre-unconformity sedimentary section beneath Santa Rosa and Santa Cruz-Catalina Ridges and the deeper depth of erosion across the unconformity beneath the current bathymetric basin, implies that post-Miocene basin inversion has also contributed to the current configuration of Borderland seafloor topography.

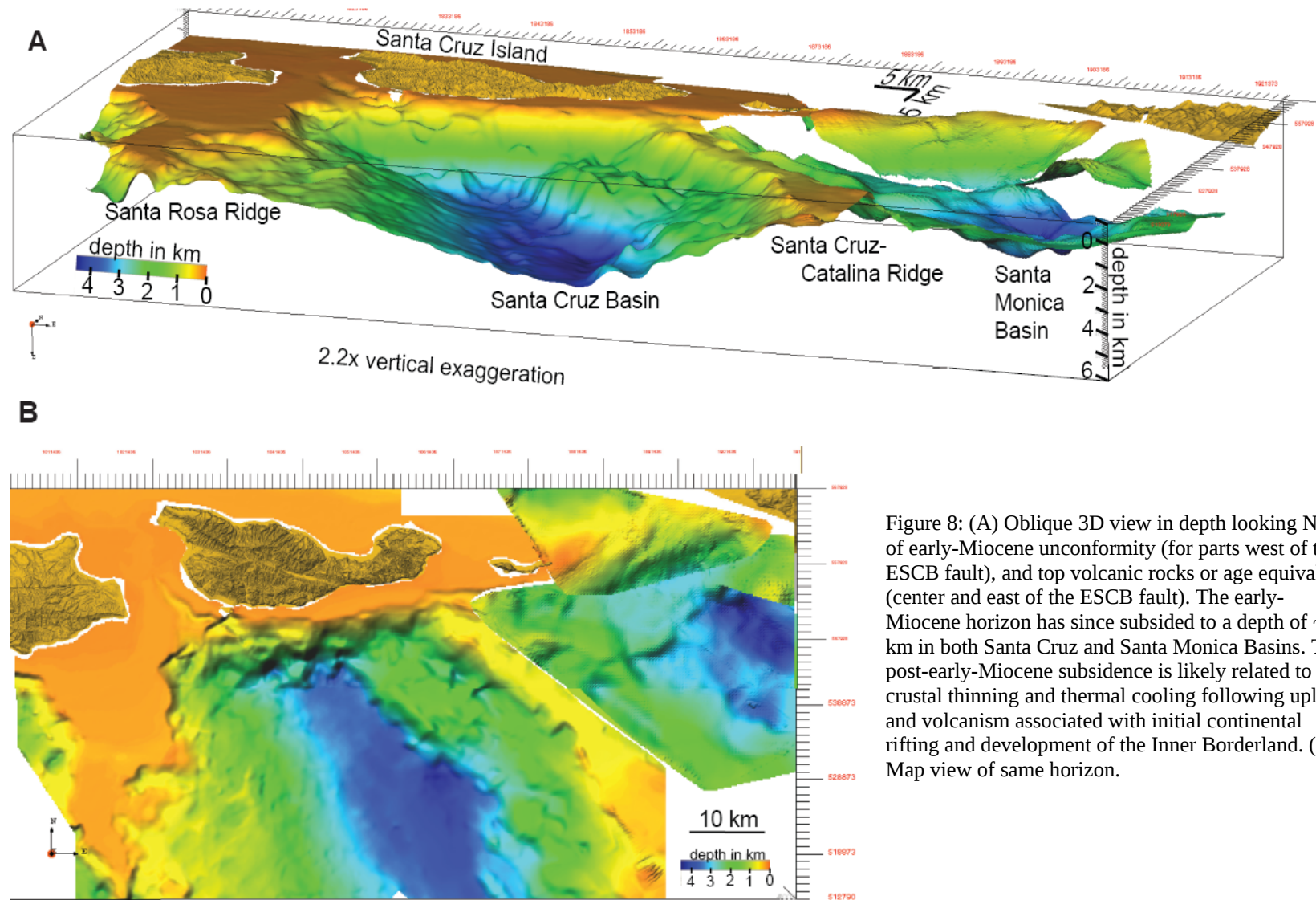


Figure 8: (A) Oblique 3D view in depth looking NNW of early-Miocene unconformity (for parts west of the ESCB fault), and top volcanic rocks or age equivalent (center and east of the ESCB fault). The early-Miocene horizon has since subsided to a depth of ~4 km in both Santa Cruz and Santa Monica Basins. This post-early-Miocene subsidence is likely related to crustal thinning and thermal cooling following uplift and volcanism associated with initial continental rifting and development of the Inner Borderland. (B) Map view of same horizon.

Distribution of Forearc Basin Rocks and the Eastern Extent of the Nicolas Terrane

Mapping of Cretaceous-Paleogene forearc basin sedimentary rocks (GVS equivalent) characteristic of the Nicolas terrane shows that these strata pinch out to the northeast beneath Santa Cruz basin as they approach the ESCB fault (Figures 7 & 9) and then reappear on Santa Cruz-Catalina Ridge. These forearc basin rocks apparently truncate downward or downlap eastward against basement on seismic reflection profiles displayed in two-way travel time (Figure 7). A restoration of the depth-converted early-Miocene unconformity to its original, presumed, paleo-horizontal orientation reveals onlap of the forearc basin rocks onto basement (Figure 10). The pinch-out is then formed by the combination of erosion into the top of these forearc rocks, as shown by the early-Miocene unconformity, and this original basement onlap surface. More importantly, reconstruction of the original forearc basin geometry provides an important reference frame against which to evaluate subsequent patterns of plate boundary deformation.

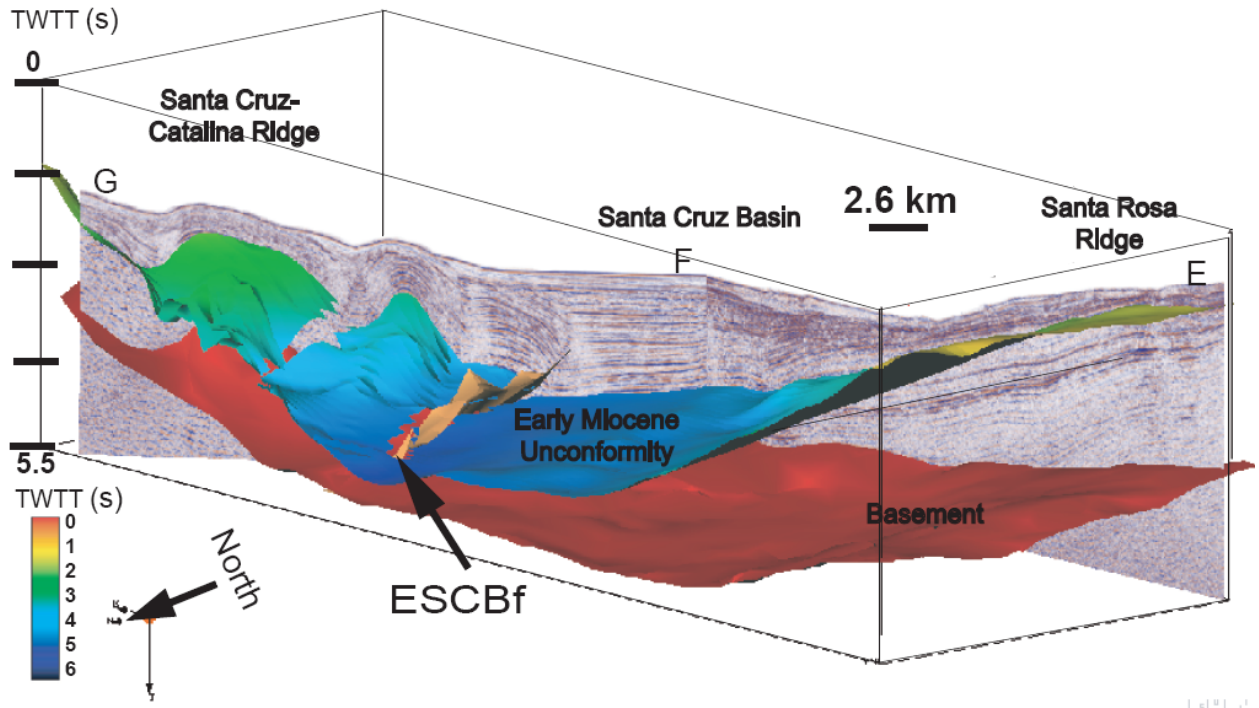


Figure 9: Oblique 3D view (Composite profile E-F-G located on Figure 2) looking south of the early-Miocene unconformity (blue-green) and top basement (red) surfaces across the northeast-dipping East Santa Cruz Basin (ESCB) fault system. The unconformity generally represents the top or near top of GVS (Cretaceous-Paleogene forearc basin rocks). The ESCB fault system was previously thought to be the eastern boundary of the Nicolas terrane, but the presence of these older forearc basin rocks on Santa Cruz-Catalina Ridge indicates that the actual terrane boundary lies farther east.

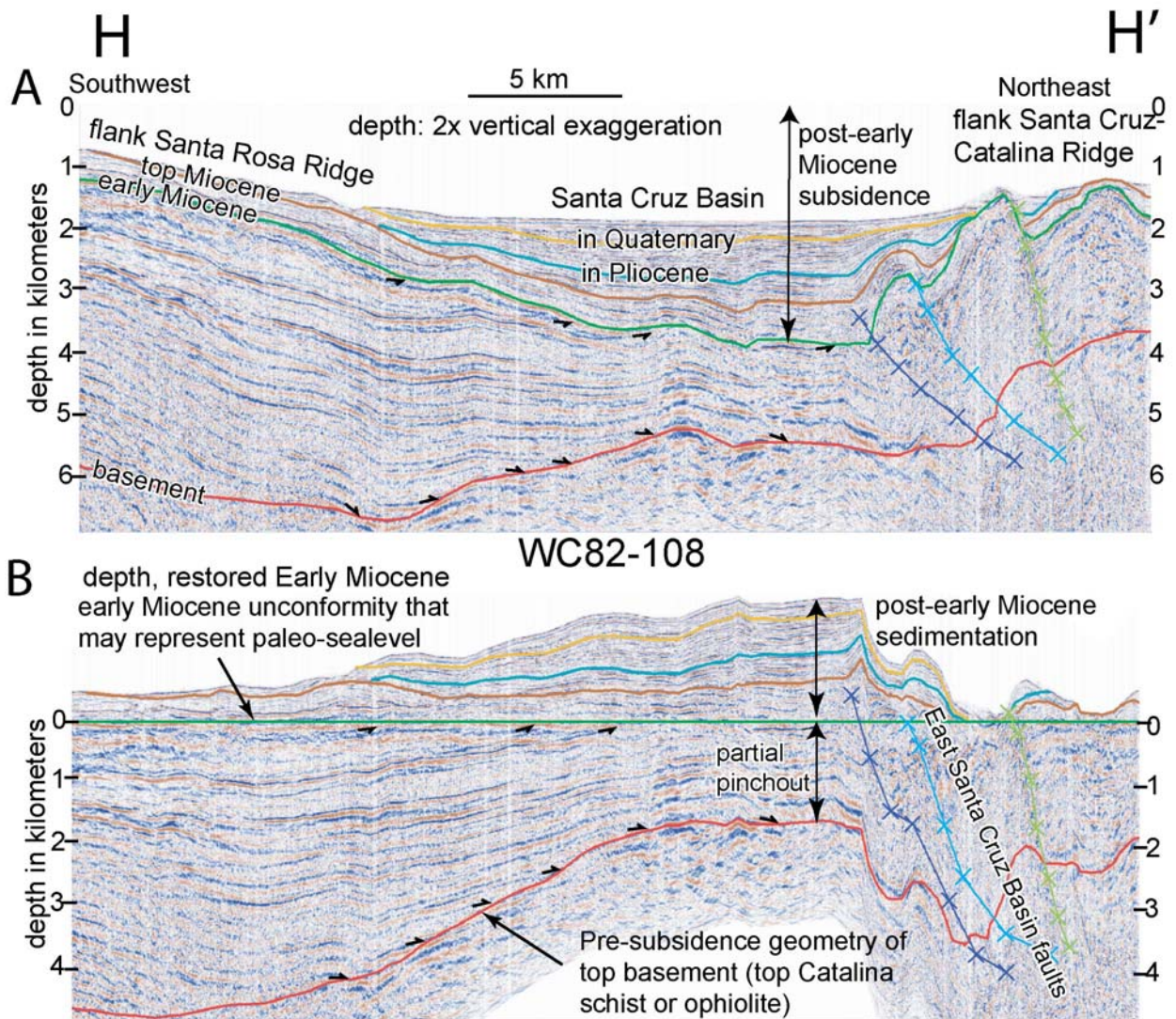
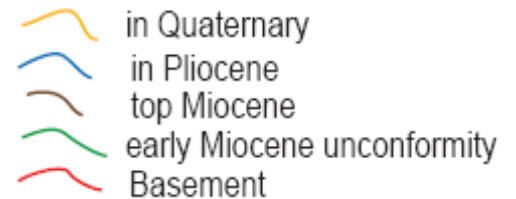


Figure 10: (A) Seismic section WC82-108, located in Figure 2, converted to depth and (B) flattened along the early-Miocene unconformity (green). This flattening emphasizes basement topography and forearc basin strata onlap (arrows) prior to subsequent basin subsidence and sedimentation, as well as subsequent folding and basin inversion along Santa Rosa and Santa Cruz-Catalina Ridges. Such structural modeling can help with basin and plate reconstructions to quantitatively evaluate vertical and lateral motions associated with Pacific-North American plate boundary evolution.



Characteristics of the East Santa Cruz Basin (ESCB) fault system

The ESCB fault system separates Santa Cruz basin from Santa Cruz-Catalina ridge. It is now interpreted to be a gently east- to northeast-dipping, right-stepping, en-echelon reactivated reverse or oblique-reverse fault (Figures 5, 7, 9, 10, 11), with evidence for apparent earlier Miocene normal separation, that bends gently to the west and dips northerly as its strands approach the northern Channel Islands (Figure 12, 13). Both Great Valley Sequence (GVS) equivalent (Cretaceous and Paleogene) and younger (Miocene age) sedimentary rocks exist in both the hanging wall and footwall of this fault system (Figure 10, 12). The GVS pinches out towards the east in the footwall beneath Santa Cruz Basin (Figures 5, 7, 9 & 10) and reappears as a thicker stratigraphic section in the hanging wall on Santa Cruz-Catalina Ridge (Figures 5, 7, 9, 10 & 11). In contrast, post-Miocene sedimentary rocks in the footwall of the ESCB fault system (in Santa Cruz Basin) are relatively thick and onlap onto the flank of Santa Rosa Ridge (Figures 7, 10 & 11), while these post Miocene rocks are thin to nonexistent in the hanging wall (Figures 5, 7, 10, 11).

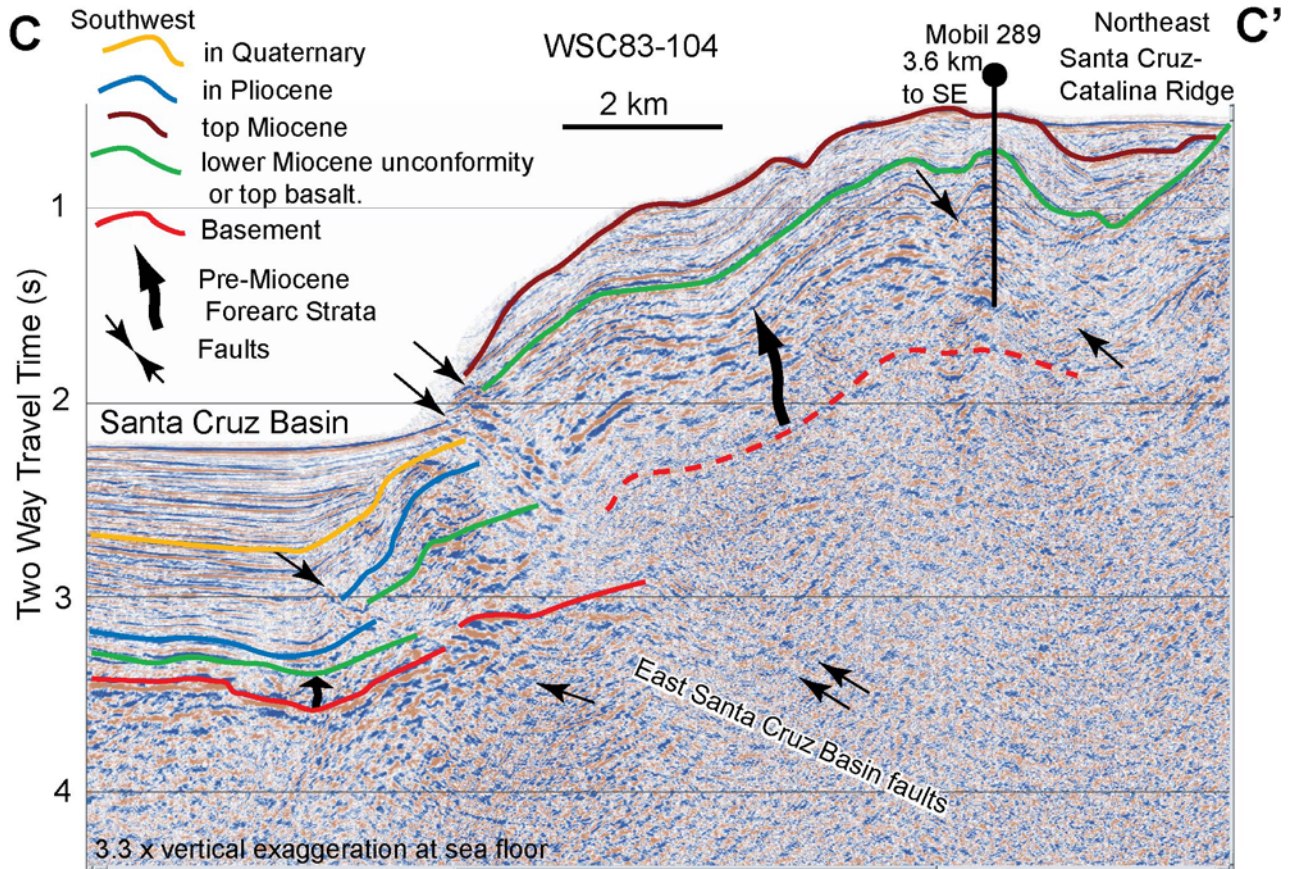


Figure 11: Seismic profile WSC83-104, C-C' (located on Figure 2) showing Miocene strata thin in the footwall (middle and late Miocene is missing or mostly missing) of the gently east-dipping East Santa Cruz Basin fault system (black paired arrows) and thick in the hanging wall as are the Cretaceous-Paleogene forearc basin strata. This is consistent with the east-dipping ESCB fault system originally accommodating Miocene extension and normal separation, followed by post-Miocene basin inversion. The presence of forearc basin rocks of the Nicolas terrane on Santa Cruz-Catalina Ridge indicates that the East Santa Cruz Basin fault system is unlikely to be the major boundary between the Nicolas and Catalina terranes, or that it accommodated large lateral displacements.

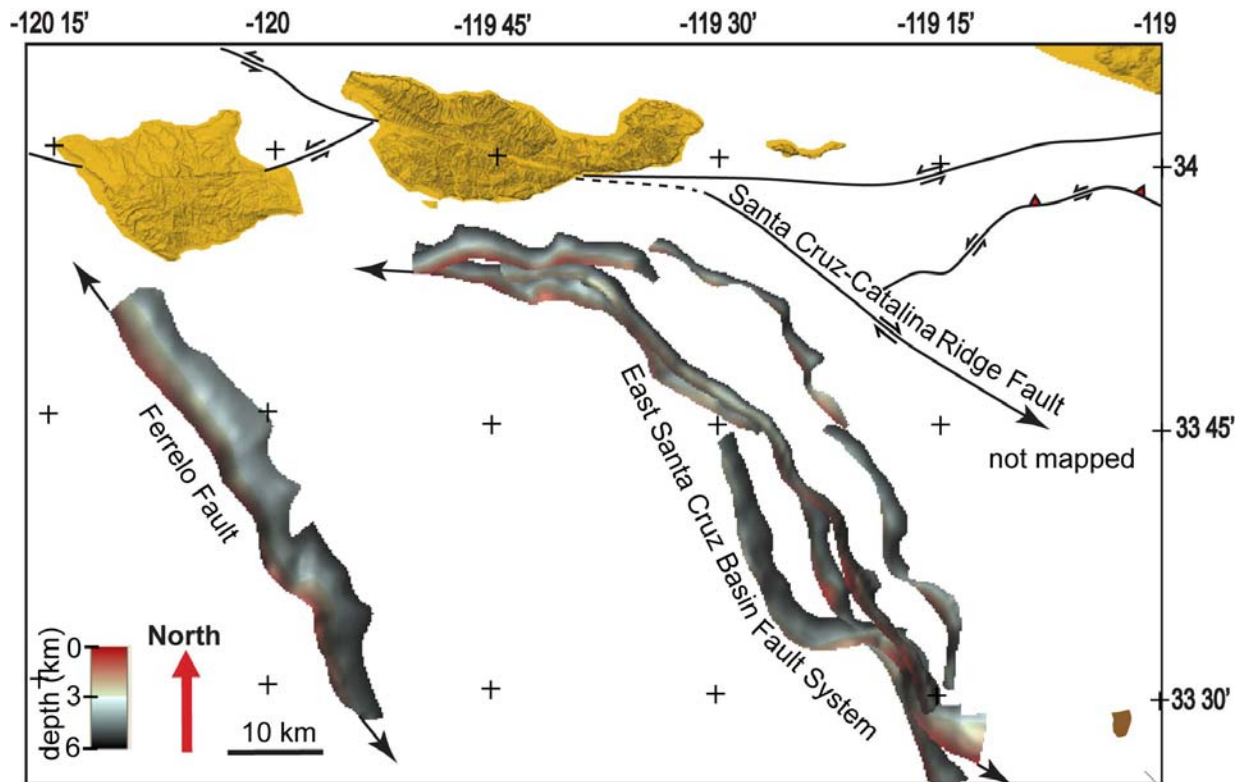


Figure 12: A map view of 3D fault surfaces surrounding Santa Cruz basin in the northern Borderland. Depths down-dip along fault surfaces are shown as changing colors at even kilometer levels. The ESCB fault system is observed to be a gently east- to northeast-dipping, right stepping, en echelon reactivated reverse or oblique-reverse fault that bends to become more northerly dipping as it approaches Santa Cruz Island.

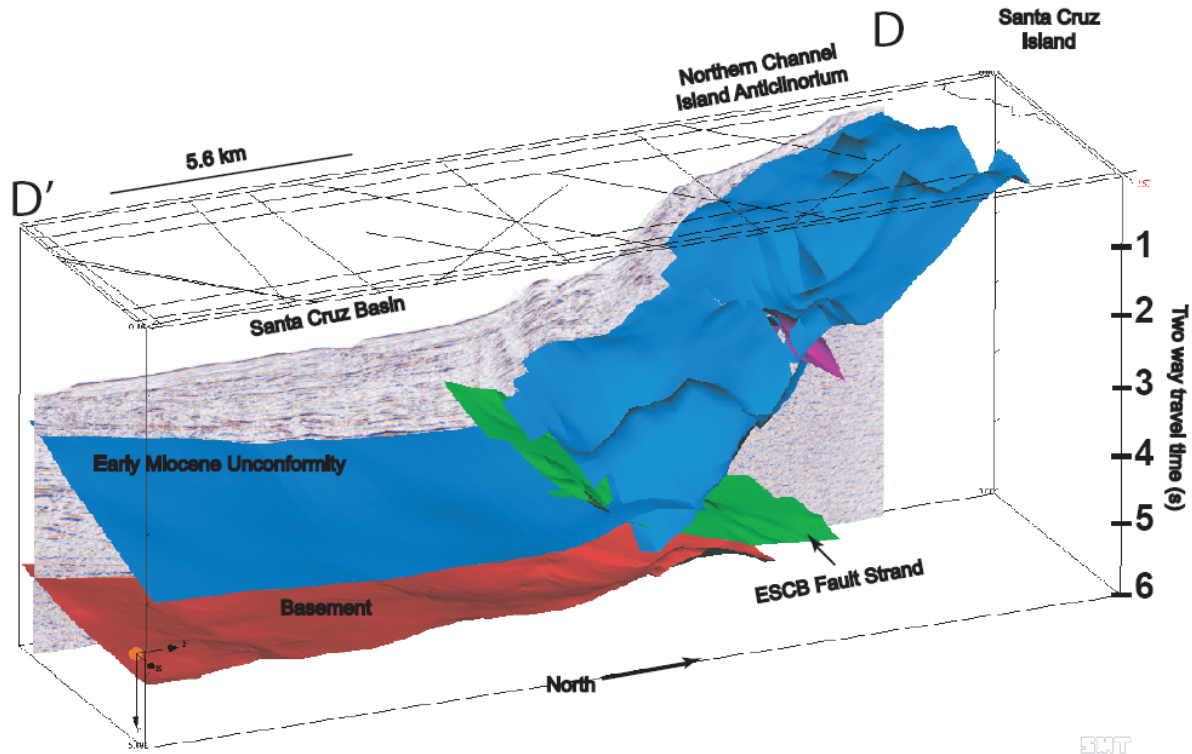


Figure 13: Oblique view looking west across a strand of the East Santa Cruz Basin fault system just south of Santa Cruz Island (D-D', location in Figure 2). At this location, this arcuate fault segment strikes west, is north dipping, and has been over-ridden by the Northern Channel Islands anticlinorium from the north.

Discussion

The new observations and revised interpretations for the northern Outer Borderland suggest that existing models of Borderland deformation may need to be modified. These revised models of Outer Borderland structure and tectonics must accommodate: (1) evidence for significant vertical motions that imply large-scale regional uplift, basin subsidence, and subsequent basin inversion in the northern Outer Borderland; (2) a change in the interpreted geometry of the Nicolas-Catalina terrane boundary and the subsequent distribution of pre-rift forearc basin rocks; (3) a revised interpretation for the geometry ESCB fault system.

The primary evidence for significant vertical motions in the Outer Borderland is the existence and current configuration of the early-Miocene unconformity mapped in this project. The nature of this inferred, paleo-horizontal, near paleo sea-level feature implies

that this area must have undergone some initial regional uplift to form the unconformity, possibly when the Outer Borderland rifted away from the Peninsular Ranges in northern Baja Mexico around 17.5 Ma (Nicholson, *et al.*, 1994). Middle and late-Miocene sediments overlying the unconformity are conformable and parallel bedded implying that this uplift was followed by subsidence and that this initial Miocene subsidence was equivalent to at least the minimum observable post-unconformity, parallel-bedded sedimentary thickness of about 500 m. The parallel bedding exists across both Santa Rosa Ridge and Santa Cruz Basin (Figure 5, 7, 10) suggesting that this initial subsidence was uniform and regional. The increased and localized subsidence, which led to the formation of Santa Cruz Basin, prevented continued deposition farther west on what would become Santa Rosa Ridge and initiated the onlap of younger post-Miocene basin sediments onto that structural high. Total subsidence in Santa Cruz basin of the unconformity since its original inception near sea level is approximately 4 km (Figure 8).

Farther east in Santa Monica Basin (Figure 8), this same or age-equivalent erosional surface has been interpreted to have experienced a similar amount of basin subsidence (~4 km). However, unlike Santa Cruz Basin, Santa Monica basin experienced large-scale crustal exhumation and denudation as part of Inner Borderland rifting, and is still an area of high heat flow (Crouch and Suppe, 1993; Bohannon and Geist, 1998; ten Brink, *et al.*, 2000). Thermal cooling and a larger sediment load can account for some of the subsidence seen in Santa Monica basin, but these processes cannot account for the equivalent amount of subsidence seen in Santa Cruz Basin, as this basin did not experience the same large scale crustal extension or large sediment load as Santa Monica Basin. Tectonic loading from adjacent highs cannot account for much of the observed basin subsidence either, as Santa

Cruz basin and both Santa Rosa and Santa Cruz-Catalina Ridges were all at or near paleosea-level in early-Miocene time. It is likely therefore, as suggested by Miller (2002) and ten Brink *et. al* (2000), that the flow of lower crustal material to the east as part of the exhumation and formation of the Inner Borderland metamorphic core complex caused localized crustal thinning within the lower crust. This localized crustal thinning was a major contributor to the enhanced subsidence increasing towards the east seen in Santa Cruz Basin (Figure 8).

The subsequent folding of the early-Miocene unconformity, cessation of subsidence of Santa Rosa Ridge and localization of post-Miocene sediments in Santa Cruz basin suggest that this Miocene phase of transtension was followed by transpression starting in early-Pliocene time. Regionally, transpression and the onset of folding also began near the beginning of Pliocene time (~5-6 Ma). This includes shortening of the northern Channel Islands and deformation within the Santa Barbara Channel and offshore Santa Maria Basin (Clark *et al.*, 1991; Seeber and Sorlien, 2000). This regional transpression was associated with a reorganization of the plate boundary into the Gulf of California and the creation of the southern San Andreas fault (Atwater, 1989; Oskin and Stock, 2001), as well as an inferred change in Pacific plate motion vector relative to fixed NAM (Atwater and Stock, 1998, Wilson *et al.*, 2005).

A key observation related to this change from transtension to transpression is the reversal of direction of the pinch-out of post-Miocene sedimentary rocks (to the west/southwest) compared to the pinch-out of the Paleogene-Cretaceous (Nicolas terrane) forearc basin rocks (to the east/northeast). These post-Miocene rocks thin by onlap onto the flank of Santa Rosa Ridge, in contrast to the parallel-bedded Miocene rocks beneath (Figure

5, 7). This onlap implies the initiation of the growth of Santa Rosa Ridge, or the differential subsidence between Santa Cruz Basin and Santa Rosa Ridge, and an inversion of the preexisting forearc basin, occurred at this time. Chaytor *et al.* (2008) used paleoshorelines as strain markers for Holocene and late Pleistocene vertical motions along the Northern Channel Islands and Santa Cruz-Catalina Ridge, finding that although the southern edge of the Northern Channel Islands is currently experiencing uplift, no significant vertical tectonic motions (uplift or subsidence) have occurred along Santa Cruz-Catalina Ridge since the last glacial maximum.

The eastern edge of the Nicolas terrane is often modeled to be fault-bounded, and the ESCB fault system is often presumed to be this terrane boundary (Crouch and Suppe, 1993; Bohannon and Geist, 1998; ten Brink *et al.*, 2000; Miller, 2002). However, Paleogene rocks in the Mobil well OCS-P-0289 on Santa Cruz-Catalina Ridge have now been correlated along seismic reflection profiles to the Paleogene-Cretaceous rocks in Santa Cruz Basin and on Santa Rosa Ridge (Figure 11). This implies that the ESCB fault system represents neither the eastern extent of forearc basin rocks that characterize the Nicolas terrane, nor has accommodated large amounts of strike-slip displacement often inferred for terrane bounding faults in the Borderland (Howell and Vedder, 1981).

The downward erosion of the early-Miocene unconformity, combined with the original depositional onlap onto basement, produced the observed pinch-out of forearc basin rocks within Santa Cruz Basin (Figures 5, 7, 9 & 10). Thus, the actual eastward termination of the forearc basin rocks that characterize the Nicolas Terrane is not controlled by the ESCB fault (Figure 9). On the other hand, gravity data imply a large density difference between the Nicolas and Catalina terranes, and the location of this major gravity gradient is coincident

with the ESCB fault system (ten Brink *et al.*, 2000; Miller, 2002). If this major change in gravity signature, which reflects more of the overall crustal composition, is taken as the primary tectono-stratigraphic terrane boundary, then this boundary is no longer coincident with the eastern extent of forearc basin rocks, or the location of inferred large lateral displacements between the Inner and Outer Borderland.

Due to the en echelon character of the ESCB fault system, it is likely that there was some right-lateral, oblique component of slip along the ESCB fault system. The thicker section of folded and inverted forearc basin rocks in the hanging wall on Santa Cruz-Catalina Ridge (Figures 10 & 11) implies, however, that the vertical component of slip changed from normal to reverse. The timing of this reversal agrees with the reversal of pinch-out observed in Santa Cruz basin between the post early-Miocene strata and the post-Pliocene and younger sediments. In addition, as the ESCB fault system approaches the northern Channel Islands, its strands bend towards the west and become north-dipping (Figures 12 & 13). This interaction of Borderland faults with the overriding western Transverse Ranges province allows this inferred oblique fault motion to contribute to the active growth of the northern Channel Islands anticlinorium (Figure 13).

Conclusions

Regional uplift associated with ridge subduction and continental rifting formed an early-Miocene unconformity that is present within Santa Cruz Basin, and on Santa Rosa Ridge. This uplift was followed by uniform regional subsidence of at least 500 m across Santa Rosa Ridge and Santa Cruz Basin. The total subsidence within eastern Santa Cruz Basin based on the present depth of the early-Miocene unconformity is about 4 km. Thermal cooling, sediment load and adjacent tectonic loading can account for a portion of the

subsidence seen in Santa Cruz Basin, but the major contributor to this subsidence was likely the increased crustal thinning of Nicolas terrane from the flow of lower crustal materials to the east as the Inner Borderland was deformed by a metamorphic core complex extension. With the onset of inferred post-Miocene transpression, growth of Santa Rosa Ridge was initiated and part of the pre-existing forearc and Miocene basin was subsequently inverted.

The pinch-out of forearc basin rocks to the east and their presence on both sides of the ESCB fault system implies that if the Nicolas-Catalina terrane boundary is taken to be either the eastern extent of forearc basin rocks or the location of large lateral displacements, then the Nicolas-Catalina terrane boundary is not the ESCB fault and is likely located farther to the east. Gravity data (ten Brink *et al.*, 2000; Miller, 2002), however, suggest that if the Nicolas-Catalina terrane boundary is defined by the overall composition of the crust and not just the distribution of forearc basin rocks, then the boundary between the Nicolas and Catalina terranes lies somewhere coincident with the ESCB fault system.

When the early-Miocene unconformity is restored to a paleo-horizontal surface, the forearc basin rocks underlying Santa Cruz Basin exhibit their original onlap configuration onto basement and the eastern forearc basin margin. This reconstructed pre-rift geometry of the forearc basin margin allows for the subsequent deformation associated with the evolving plate boundary and the ESCB fault system to be characterized. The existence of both these pre-rift and post-rift sediments and the 3D geometry of their current configuration or distribution signify a new interpretation of the ESCB fault system. The predominantly east-to-northeast-dipping ESCB fault system exhibits apparent normal separation during Miocene time. This motion was most likely oblique and included some right-lateral components of strike-slip to help accommodate the oblique rifting of the Inner Borderland and the inferred

Miocene transtensional tectonic stress regime (Nicholson *et al*, 1994; Atwater and Stock, 1998). This was followed by apparent reverse separation during fault reactivation and basin inversion in post-Miocene time.

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