Chapter 2
Tectonic history of the Transverse Ranges: Rotation and deformation on the plate boundary

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Abstract

The Santa Barbara Channel Islands are located on the western edge of the Transverse Ranges block, within the California Continental Borderland. These islands have been uplifted by faulting and folding associated with the collision of the North American and Pacific plates and the rotation of the Transverse Ranges block. Paleomagnetic data indicates that the Transverse Ranges block has rotated 80-110° from its original orientation (Kamerling and Luyendyk, 1985). This rotation occurred during the evolution of the current plate boundary, which took place in three stages: subduction, transtension and transpression. In the Mesozoic, the western edge of North America was a subduction zone with the Farallon plate subducting eastwards under the North America plate. As the spreading ridge between the Farallon and the Pacific plates approached the continental margin, spreading along the Pacific-Farallon ridge slowed as the remaining fragments of the Farallon plate were captured by the Pacific plate and began to move with Pacific plate motion - predominately northwest. This changed the continental margin from a subduction zone to a transtensional boundary. Since portions of the captured Farallon underlay North America, this change in the direction of plate motion caused several blocks of continental crust to break off, including the Transverse Ranges block and the Outer Continental Borderland. The other blocks were captured by the Pacific plate, but the Transverse Ranges block was trapped at its northern end by a step in the continental margin and so began to rotate. This rotation and extension caused extensive normal faulting and the opening of a number of basins, similar to the Basin & Range province. This rotation continued until the Pacific plate captured Baja California and began transporting it northwest, pressing its northern end against southern California. This changed the transtensional regime to a transpressional regime in the California Continental Borderland, causing extensive folding and the inversion of the existing normal faults to reverse. These processes of folding and uplift exposed and shaped the Santa Barbara Channel Islands.

Introduction

The coast of southern California is located on a transpressional plate boundary between the Pacific and North America plates. The Pacific plate is moving northwest relative to North America at around 48 mm/year (Jackson and Molnar, 1990). This motion is accommodated largely through the San Andreas Fault system and sea floor spreading in the Gulf of California. The San Andreas is primarily a right-lateral transform fault with two transpressional bends to accommodate that aspect of plate motion, while spreading in the Gulf of California accommodates the transtensional aspect.

The development of this plate boundary took place in three stages. In the Early Miocene, the west coast of North America was a subduction zone, with the Farallon plate subducting under the North America Plate. At ~30 Ma, the spreading center between the Pacific and Farallon plates first made contact with North America, and the direction of relative plate motion shifted to oblique transtension. With this change in tectonic regime came crustal extension, faulting, and extensive volcanism in the California Continental Borderland as remnants of the Farallon plate and blocks of continental crust broken off of North America were captured by the Pacific plate and transported northwest relative to North America. The Transverse Ranges block was among those which broke off, but was trapped at its northern end by a bend in the plate boundary, while its southern end could move freely, causing the block to rotate clockwise. This continued until ~5 Ma, when the Pacific plate captured Baja and began pressing its northern end against Southern California, changing the plate boundary in the Borderland to a transpressional regime with extensive folding and normal faults inverted to reverse.

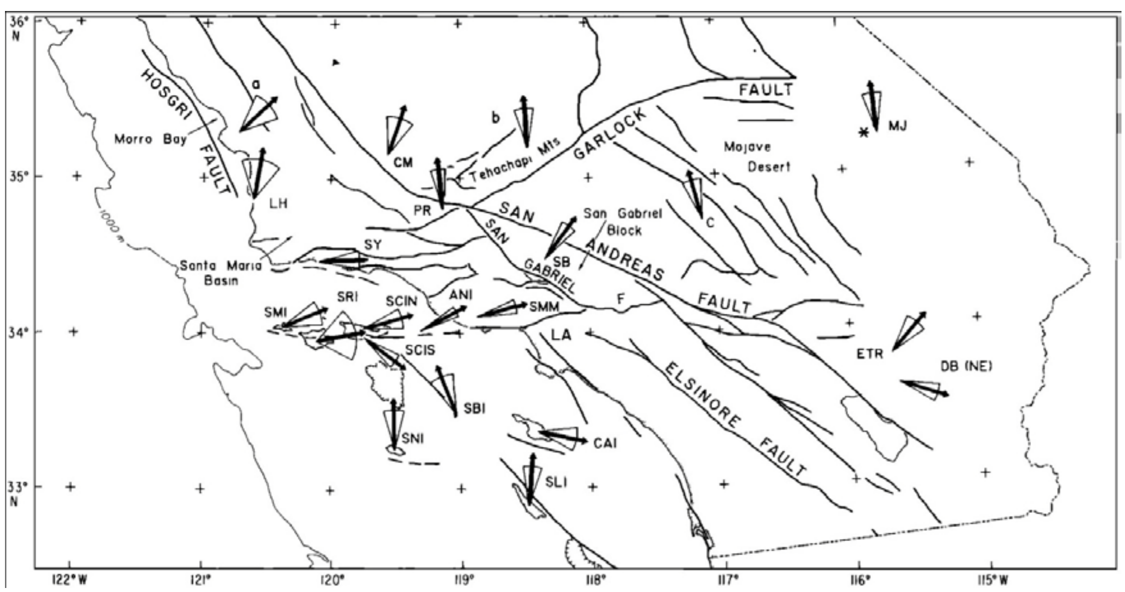

Figure 2.1. Paleomagnetic declinations of Neogene rocks in Southern California demonstrating rotation of the Transverse Ranges Block. ETR, Eastern Transverse Ranges; SLI, San Clemente Island; CAI, Catalina Island; SNI, San Nicolas Island; SBI, Santa Barbara Island; SMI, San Miguel Island; SRI, Santa Rosa Island; SCIN, north Santa Cruz Island; SCIS, south Santa Cruz Island; ANI, Anacapa Island; LA is the City of Los Angeles (Luyendyk, 1985).

Background

The east-west oriented Transverse Ranges present an anomaly in southern California where all the other mountain ranges are oriented parallel to the strike of the San Andreas fault. Paleomagnetic and geologic data indicates that the Transverse Ranges crustal block was originally oriented north-south and located near the latitude of present day San Diego and Anaheim (Figure 2.1) (Kamerling and Luyendyk, 1985). During the evolution of the Pacific-North America plate boundary, the Transverse Ranges broke off of North America and rotated as a cohesive block 80-110° clockwise to its present position (Kamerling and Luyendyk, 1985). This process of rotation, with its associated faulting, folding, and crustal upwelling also formed the California Continental Borderland. The Borderland is a series of basins and ridges bounded by major faults, similar to the Basin & Range province. It is largely submerged and located on the continental shelf of southern California. The Santa Barbara Channel Islands occur where these ridges protrude above sea level. The Outer Continental Borderland started as another block broken off of North America and captured by the Pacific plate while the Inner Continental Borderland is composed of metamorphic basement rocks which rose to fill the slab window opened in the wake of the rotating Transverse Ranges, as illustrated in Figure 2.2.

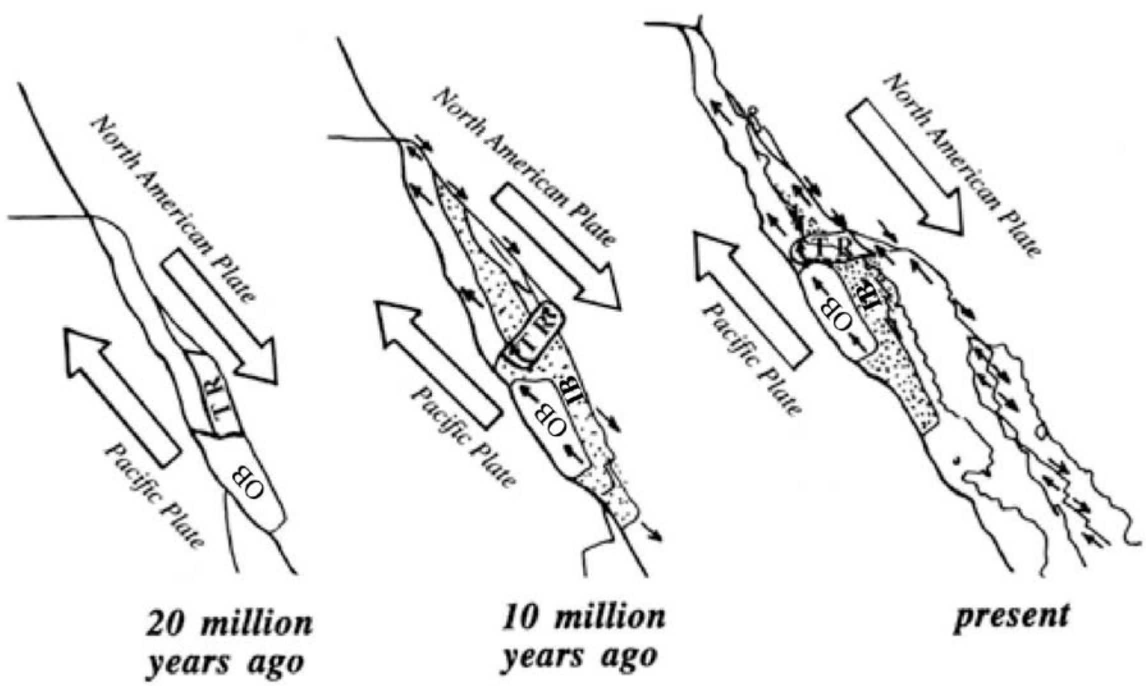

Figure 2.2. Tectonic History of the Transverse Ranges (TR), Outer Borderlands (OB), and Inner Borderlands (IB) showing left to right (1) the initial collision of the Pacific and North America plates, (2) transtension and the rotation of the Transverse Ranges Block and (3) transpression, the current San Andreas dextral transform fault system, and the extrusion of the Transverse Ranges block around the larger transpressional bend of the San Andreas (after Atwater, 1998).

Tectonic History

The tectonic history of the Transverse Ranges and the California Continental Borderland can be divided into three regimes: subduction, transtension and transpression (Figure 2.2). These three regimes represent different stages in the development of the Pacific-North America plate boundary.

Subduction

In the Mesozoic, the western coast of North America was in the forearc of a subduction zone where the Farallon plate was subducting obliquely under the North America plate (Atwater, 1998). A large amount of subduction took place during this era as an area roughly the size of the contemporary Pacific Ocean was subducted under North America. The Outer Continental Borderland was located on the continental shelf collecting continental shelf sediments (Nicholson et al., 1994).

In the mid-Cenozoic, ~30 Ma, the spreading center between the Farallon and the Pacific plates approached the North America plate boundary (Atwater, 1998). As the spreading center approached, the remaining Farallon plate began to fragment, forming the Monterey, Arguello, Magdalena, and Guadalupe microplates. The Transverse Ranges and the Outer Continental Borderland experienced uplift and rifting during this time, possibly caused by the subduction of the younger, more buoyant lithosphere near the spreading center or the postulated detachment of the Monterey plate from the older, colder, subducting Farallon slab. Spreading between the Pacific and the Monterey and Arguello platelets slowed dramatically and then stopped as first the Monterey and then the Arguello microplate was captured by the Pacific plate and began to move with Pacific plate motion (Nicholson et al., 1994).

Transtension

During most of the Miocene the Continental Borderland was the site of the transtensional portion of the plate boundary motion (Atwater, 1998). The Pacific plate first made contact with North America around 28 Ma. As this happened, the relative plate motion vector between the Monterey plate and the North America plate began to rotate away from predominately east-northeast oblique subduction towards northwest transtensional transform motion. Since a good part of the Monterey plate had already been subducted, this change in plate motion subjected parts of the overriding North America plate to basal right-lateral shear and crustal extension (Figure 2.3). Since the partially subducted Monterey plate was now moving northwest with Pacific plate motion and dragging the overlying North American continental crust with it, the Pacific-North America plate boundary shifted from the continental margin to within the continent. As this happened, the basal shear generated by the captured Monterey plate separated three north-south oriented blocks of continental crust from North America. The two outer blocks, the Santa Lucia Bank and the Outer Continental Borderlands, became attached to the Pacific plate and have been transported obliquely up the coast and slightly seaward (Atwater, 1998). The third block, the Transverse Ranges, was trapped at its northern end against the North America plate by a bend in the plate boundary and, as a consequence, began to rotate clockwise, inserting its southern end between the other two blocks (Figures 2.2 and 2.3). Because it was riding largely on the subducted Monterey plate, now captured by the Pacific, it was able to rotate as a cohesive block (Nicholson et al., 1994).

In the wake of the rotating Transverse Ranges block, a slab window opened as the Pacific plate pulled the Santa Lucia Bank, the outer Continental Borderlands and the southern end of the Transverse Ranges away from North America (Figure 2.3). This extreme extension led to thinning of the overlying continental crust. The gap was filled from below by igneous rocks and metamorphosed, underplated Franciscan rocks, such as the Catalina schist, which rose in a ductile manner (Figure 2.4) (Atwater, 1998).

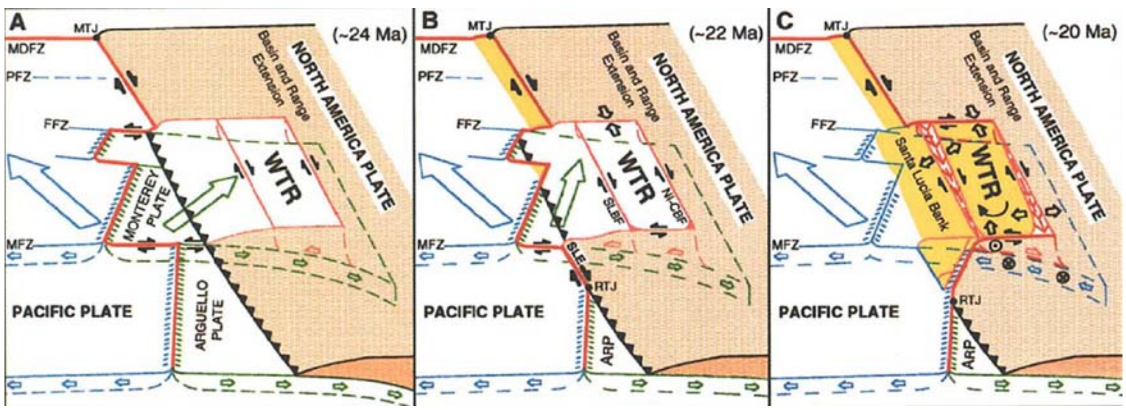

Figure 2.3. Capture of the Monterey plate by the Pacific plate showing directions and magnitudes of relative plate motions. **(A)** Monterey and Arguello (A_RP) microplates subducting under North America. **(B)** Spreading between the Monterey and the Pacific plates slows, and the direction of relative plate motion begins to rotate. **(C)** Full capture of the Monterey plate by the Pacific plate, detachment of the Santa Lucia Bank (SLBF) and Transverse Ranges (WTR) from North America by basal shear, and slab windows opening as the Transverse Ranges begin to rotate (Nicholson et al., 1994).

This area of extension became the Los Angeles Basin and the Inner Continental Borderland (Figures 2.2 and 2.5). The region is characterized by extensional structures such as hanging-wall blocks, horsts, and half grabens similar to the Basin and Range province (Atwater, 1998). This extension process opened numerous isolated basins which created the distinctive environment for the deposition of the Monterey formation and other younger marine deposits (Nicholson et al., 1994). The crustal thinning also caused decompressional melting and upwelling in the asthenosphere which triggered regional volcanism and the deposition of extensive Miocene volcanics, including the Santa Cruz Island Volcanics (see Chapter 3).

Transpression

While the Transverse Ranges block was rotating, the Pacific-North America transform margin was well established on the Pacific side of Baja California, creating a transtensional margin. A tectonic reorganization occurred at about 5 Ma when the Pacific plate captured the Magdalena and Guadalupe microplates, remnants of the Farallon plate which had been subducting under Baja (Figure 2.5). As the motion of the Guadalupe and Magdalena microplates relative to North America shifted from oblique subduction to the predominantly north-west motion of the Pacific plate, this applied tension to Baja and led to the Pacific plate's capture of Baja California through the same mechanism of basal traction that had led to the capture of the Outer Continental Borderlands (Nicholson et al., 1994). This abruptly shifted the southern end of the Pacific-North America contact into what is now the Gulf of California and caused the plate boundary to break a new path across southern California to reconnect to its northern terminus, forming the present San Andreas Fault system.

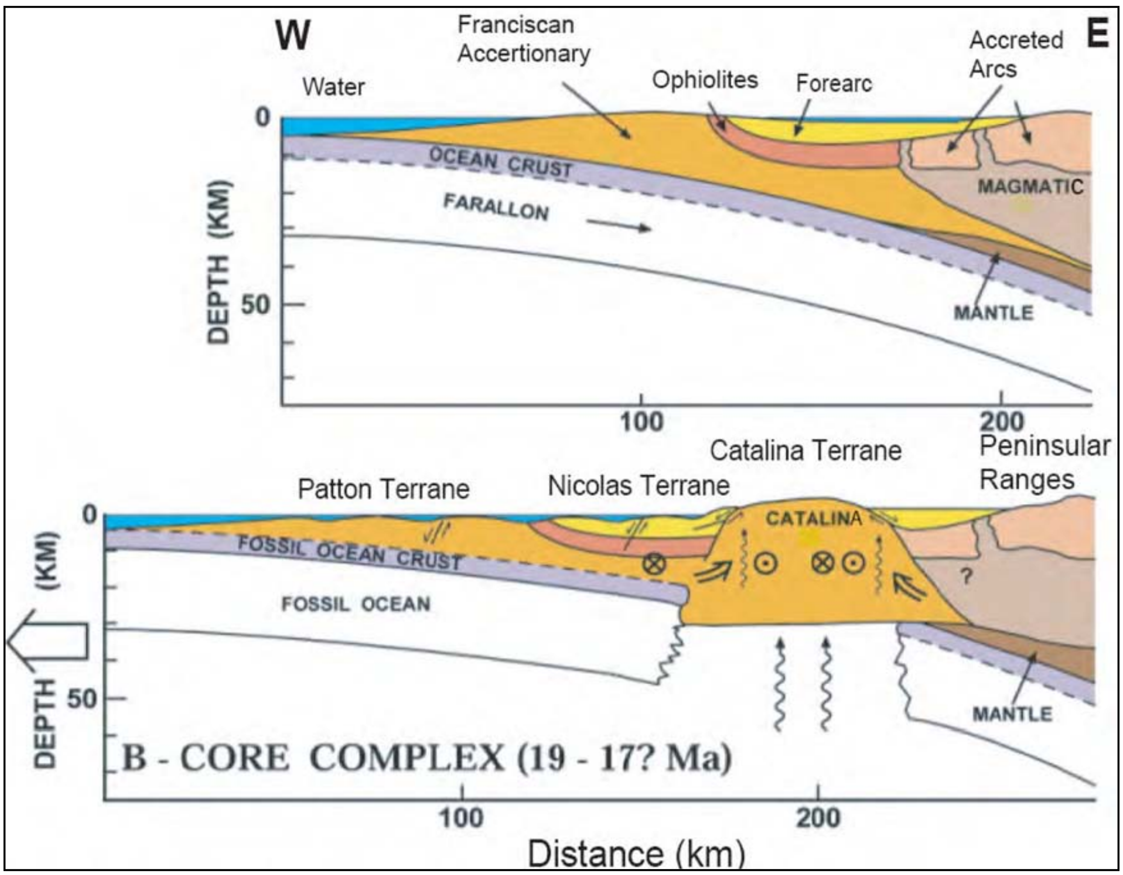

Figure 2.4. Change in the relative motion of the Monterey plate causing a slab window to open, emplacement of the Catalina Schist, and formation of the Inner Continental Borderlands (Schindler, 2010).

Since everything around Baja was already moving with Pacific plate motion, it did not rotate but was transported northwest, causing spreading in the Gulf of California, and ramming its northern end into southern California. The pressure of Baja pushing northwest created the two transpressional bends in the San Andreas and changed the tectonic regime in the Continental Borderlands from transtensional to transpressional. In this new configuration, the Transverse Ranges block is trapped at its eastern end against the larger of the two transpressional bends in the San Andreas and is being extruded westward around it and shortened north-south (Figures 2.2 and 2.5). To accommodate the westward-extension, major left-lateral faults, including the Santa Cruz Island Fault, have formed along the southern edge of the block. North -south shortening is accommodated through extensive folding and various Miocene normal faults inverted to reverse faults (see Chapter 4). At the southern edge of the Transverse Ranges, a blind thrust fault system underlying the Santa Barbara Channel and left-lateral faults caused the uplift and deformation of the Northern Channel Islands. Deformation structures include major folds and many levels of submarine and subaereal, tilted marine terraces formed by changes in sea level and the islands elevation (see Chapter 5). These effects are particularly prominent in the Inner Continental Borderland and are well exhibited on the Santa Barbara Channel Islands.

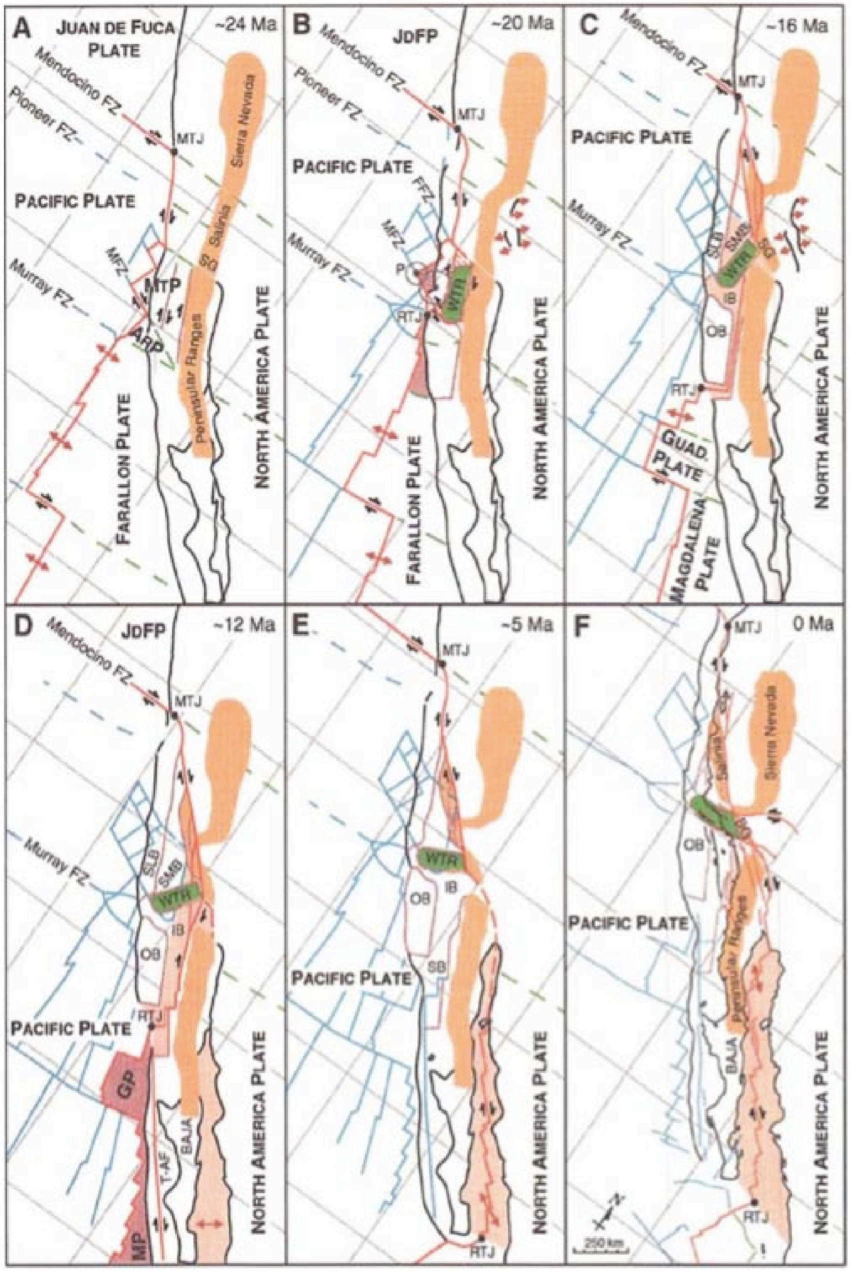

Figure 2.5. **[A]** Farallon-North America subduction showing collision of the Pacific and North America plates and fragmentation of the Farallon plate into the Arguello (A_RP) and Monterey (M_TP) microplates. **[B]** Beginning of transtensional phase. Capture of the Monterey and Arguello microplates by the Pacific plate. Separation of the Transverse Ranges (WTR), Santa Lucia Banks (SLB), and Outer Borderlands (OB) from North America and the beginning of rotation. **[C]** Continued rotation of the Transverse Ranges causes slab windows to open, and intrusion of the Inner continental Borderlands. The Farallon plate continues to fragment into the Magdalena (MP) and Guadalupe (GP) microplates. **[D]** Spreading begins in the Gulf of California. Transform boundary well established on the Pacific side of Baja. **[E]** Capture of the Magdalena and Guadalupe microplates and Baja California by the Pacific plate. Plate boundary realigns through southern California. **[F]** Baja is transported northwest, pressing its northern end against southern California and shifting to a transpressional tectonic regime with the Transverse Ranges being extruded around the larger transpressional bend of the San Andreas and shortened north-south (Nicholson et al., 1994).

Conclusion

The rotation and deformation of the Transverse Ranges played a crucial role in shaping the current geology of the California Continental Borderland and creating the Santa Barbara Channel Islands. The collision of the Pacific and North America plates and the subsequent transtensional tectonic regime, separated the Outer Continental Borderlands and the Transverse Range from North America, and caused the rotation of the Transverse Ranges as a cohesive crustal block. This transtensional regime also caused normal faulting the opening of numerous isolated basins which formed the environment for the deposition of the Monterey Formation. As the Transverse Ranges rotated, the slab window that opened in their wake provided the mechanism for the emplacement of the Catalina Schist and the eruption of extensive Miocene volcanics. With the Pacific plate's capture of Baja California, the tectonic regime in the Continental Borderlands shifted to transpressional, causing folding and the inversion of the Miocene normal the Santa Barbara Channel Islands faults to reverse. This faulting and compression caused the uplift, exposure, and deformation of

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