Microplate capture, rotation of the western Transverse Ranges, and initiation of the San Andreas transform as a low-angle fault system

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ABSTRACT

Tectonic rotation of the western Transverse Ranges block is explained by capture of the partially subducted Monterey microplate by the Pacific plate at about anomaly 6 time (ca. 20 Ma). As Pacific-Monterey spreading slowed and eventually ceased, the slip vector along the gently northeast dipping subduction interface beneath the California margin changed from slightly oblique subduction to transtensional dextral transform motion. This change in slip vector and a shift of Pacific plate motion eastward along the already subducted Monterey plate interface imply that the San Andreas transform began as a system of low-angle faults that locally subjected the overriding continental margin to distributed basal shear and crustal extension. This basal shear produced the rotated western Transverse Ranges. This model helps explain the timing of initial rotation and basin formation, the sudden appearance of widely distributed transform motion well inland of the margin in early Miocene time, why the western Transverse Ranges uniquely rotated as a large coherent crustal block, and several fundamental structural characteristics of central and southern California. The model also provides major constraints on the amount of Pacific–North America strike-slip motion, the position through time of offshore oceanic plates relative to onshore geology, and a general explanation for what may happen as a spreading ridge approaches a trench and the subduction zone evolves into a transform system.

INTRODUCTION

The western Transverse Ranges are a unique feature of the California margin. The structural fabric and local fault slip vectors of this province trend at unusually high angles to the regional northwest-striking right-lateral San Andreas shear system. Geologic evidence and paleomagnetic data, as well as recent geodetic and seismicity data, indicate that the western Transverse Ranges have rotated substantially since early Miocene time and are continuing to rotate today (Crouch, 1979; Kamerling and Luyendyk, 1979, 1985; Hornafius et al., 1986; Jackson and Molnar, 1990). This rotation has been closely linked to the evolving Pacific–North American transform boundary and, recently, to large-scale extension and rifting of the inner California Continental Borderland (Crouch and Suppe, 1993). However, it has never been adequately explained why the western Transverse Ranges should accommodate such plate-boundary deformation by tectonic rotation, nor why they should have developed when and where they did. The answer, we believe, lies in the nature of the lower crust beneath the western Transverse Ranges and the Cenozoic interactions of subducting oceanic microplates as the continental margin evolved into a transform boundary.

We propose that rotation of the western Transverse Ranges block was the direct result of capture of a remnant piece of the subducting Farallon plate (the partially subducted Monterey microplate) by the Pacific plate at about anomaly 6 time (ca. 20 Ma), when subduction of the microplate was previously inferred to have ceased (Atwater, 1989; Lonsdale, 1991). The basis for this model was the discovery that subducted parts of the Monterey microplate still extend under much of the California margin as far east as the San Andreas fault (e.g., Tréhu, 1991; Howie et al., 1993), the recent identification that the southern boundary of the Monterey microplate (the Morro fracture zone) extends beneath the northwest corner of the western Transverse Ranges block (Fig. 1) (Nicholson et al., 1992), and the observation that rotations began in early Miocene time (Kamerling and Luyendyk, 1985; Hornafius et al., 1986; Luyendyk, 1991), shortly after the transfer of the Monterey plate to the Pacific plate. This coincidence in space and time suggests a cause and effect and, if true, implies a more direct tie between motions of offshore oceanic plates and specific developments of onshore California geology than previously inferred (Atwater, 1970).

PLATE TECTONICS AND THE CALIFORNIA MARGIN

As the east Pacific ridge approached the western edge of North America, the northern end of the intervening Farallon plate began to fragment, forming the Monterey and Arguello microplates at about anomaly 10 time (ca. 30 Ma) (Atwater, 1989). Pacific-Monterey spreading slowed dramatically, and the direction rotated to become more southeastward (Fig. 1), as if the Monterey plate became partly coupled to western North America. Because Pacific-Arguello spreading was faster, a *right-lateral* transform developed between the offset spreading ridges that became the Morro fracture zone (Fig. 2). East of the Pacific-Arguello spreading ridge, motion along the Morro fracture zone between the Monterey and Arguello plates was predominantly oblique *left lateral* with a significant reverse component, and the subducted Monterey plate was systematically older, colder, and stronger than the Arguello plate. First contact between the Pacific and North America plates occurred at about anomaly 8 time (ca. 28 Ma) south of the Pioneer fracture zone, and at about anomaly 6A time (ca. 22 Ma) south of the Morro fracture zone (Fig. 2, A and B) (Lonsdale, 1991). Subduction of the Monterey plate continued until about anomaly 6 time (ca. 20 Ma), when Pacific-Monterey spreading ceased altogether (Fig. 2C) (Lonsdale, 1991), allowing the Monterey plate to accrete to the Pacific plate before the Monterey plate was fully subducted. Pacific-Arguello spreading probably continued longer—at least until about anomaly 5D time (ca. 17.5 Ma) (Fig. 1).

Capture of Monterey Plate by Pacific Plate

As Pacific-Monterey spreading decreased (at about anomaly 6A) and eventually stopped, several important events occurred. First, the relative plate motion vector between the Monterey and North America plates began to rotate away from predominantly oblique subduction toward transtensional transform motion (Fig. 2); this likely resulted in strike-slip faults developing within the overriding North America plate through strain partitioning (e.g., Fitch, 1972). This is also about the time when southwest-directed oblique extension began in what is now the Mojave area (Dokka, 1989) and the southern Basin and Range, possibly as a result of the slab gap that developed at depth between the diverging Monterey and Juan de Fuca plates (Atwater, 1989) or cessation of subduction north of the Monterey plate (Fig. 3, A and B). By the time Pacific-Monterey spreading stopped at about anomaly 6 (ca. 20 Ma), the partially subducted Monterey plate was moving fully with Pacific plate motion relative to North America, and the original gently dipping subduction interface became an oblique dextral transform plate boundary (Fig. 2C). Given the Pacific–North America plate motion vector, this subjected part of the overriding North America plate to distributed basal right-lateral shear and crustal extension.

Before anomaly 6 time (ca. 20 Ma), the eastern edge of the Pacific plate extended north along the Pacific-Arguello spreading ridge, and then northwest along what is now the southern Santa Lucia Escarpment to the Morro fracture zone, where it stepped *left* to the Pacific-Monterey spreading ridge (Fig. 2B). Once the Monterey plate joined the Pacific plate (ca. 20 Ma), however, the Pacific–North America transform boundary continued north along the previously subducted Pacific-Arguello spreading ridge (circumventing the Santa Lucia Escarpment) to the Morro fracture zone, where it then stepped *right* and dipped gently east (Fig. 2C). The transform boundary continued northward as a gently dipping interface and as a broad zone of distributed shear until the northern edge of the Monterey plate (the Farallon fracture zone) was reached. There, the plate boundary began to step *left*, back to the edge of the continental margin. The northernmost boundary to this left-stepping zone of right-lateral shear was likely the southern end of the subducted Juan de Fuca plate (Fig. 3B) and was roughly the latitude where the present northern Mojave and southern Sierra Nevada regions were then located. At the continental margin, the plate boundary joined the previously established transform that continued northwest to the Mendocino triple junction (Atwater, 1989). Within the overriding North America plate, this pattern thus formed a transtensional zone of left-lateral slip above the subducted Morro fracture zone, a transtensional zone of right-lateral shear above the down-dip eastern edge of the subducted Monterey plate (now the Pacific plate), and a transpressional zone of right-lateral shear north of the Farallon fracture zone (Fig. 2C).

Once the Monterey plate was captured by

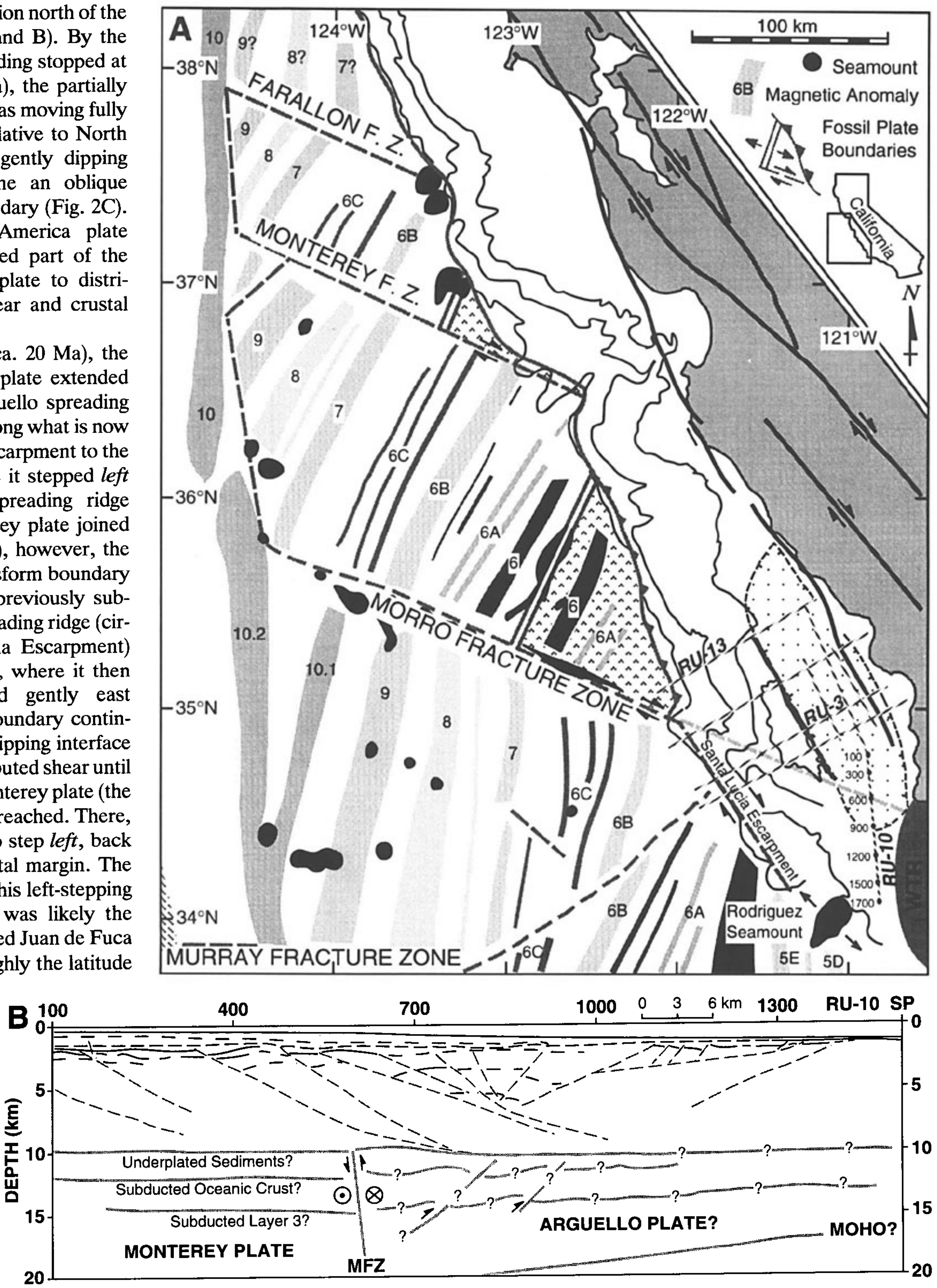


Figure 1. A: Map of magnetic anomalies offshore of central California showing Pacific-Monterey spreading, Pacific-Arguello spreading, remnant piece of partially subducted Monterey microplate captured by Pacific plate (after Lonsdale, 1991), and location of EDGE lines that image Monterey plate beneath California margin; WTR = western Transverse Ranges block. B: Depth section of RU-10, a north-south EDGE profile that images a discontinuity in lower crust that coincides with extrapolated trace of subducted Morro fracture zone (MFZ) (after Nicholson et al., 1992).

the Pacific plate, the region of the continental margin outboard of what is now the Santa Lucia Bank fault began simply to move along the plate boundary with Pacific plate motion (Fig. 3). The piece of North America farther inboard (above what was originally the Monterey plate), however, could not simply move with the Pacific plate, because it was restricted by the buttress formed by the left step of the plate boundary north of the Farallon fracture zone (Fig. 2C). As a result, it rotated. It rotated because this block—the western Transverse Ranges block—was subjected to distributed basal right-lateral shear, because its southern and eastern boundary constituted a sinistral and dextral zone of crustal extension that allowed it to rift and rotate away from continental North America (with Pacific plate motion), and because its northern boundary was effectively coupled to North America. The western Transverse Ranges rotated as a relatively coherent crustal block because it was (and, to some extent, still is) partially riding on captured (now Pacific) lower plate.

As the western Transverse Ranges block rotated (Figs. 2 and 3), the Santa Lucia Bank fault zone now became a breakaway zone for rifting and rotation, forming the western boundary of the present offshore Santa Maria basin. The eastern breakaway zone for the rotating block was probably along parts of the Coronado Bank and Newport-Inglewood fault zones (Legg, 1991; Crouch and Suppe, 1993). As the western Transverse Ranges block continued to rift, rotate, and translate northwestward with the Pacific plate, it left in its wake a region of extreme extension and crustal unroofing that became the inner California Continental Borderland (Fig. 3C) (Yeats, 1968; Crouch and Suppe, 1993). Today, this region exhibits back-tilted hanging-wall blocks, flexurally rotated detachments, horsts, and half grabens typical of the Basin and Range province (Bohannon and Geist, 1991; Legg et al., 1992; Crouch and Suppe, 1993), and high-angle strike-slip faults and young folds consistent with Miocene transtensional rifting overprinted by post-Miocene transpression (Legg, 1991; Luyendyk, 1991; Crouch and Suppe, 1993).

Continued Microplate Capture and Margin Evolution

This process of microplate capture may explain how other parts of the California margin became accreted to the Pacific plate as the Rivera triple junction continued to move south and the plate boundary continued to evolve into a transform system. Between anomalies 5C and 5D (17–18 Ma), the triple junction jumped nearly 300 km southeast along the paleotrench (Lonsdale, 1991). This permitted the capture of the Arguello microplate by the Pacific plate with the northernmost piece of the Farallon plate, resulting in the rifting and translation of the outer borderland away from northern Baja California (Fig. 3C). The outer borderland block did not rotate as the western Transverse Ranges did, because everything directly north of the outer borderland was already moving with Pacific plate motion. Thus, there was no buttress to couple or pin the northern edge of the outer borderland block to North America and cause it to rotate. Because the outer borderland did not join the Pacific plate until ~2 m.y. after the Monterey plate, the northern edge of the outer borderland became separated by about 80–100 km southeast from its original inferred position against the southern Santa Lucia Bank (Fig. 3C).

Between anomalies 5A and 5B (ca. 14 Ma), spreading along the northern East Pacific Rise again began to slow as younger, more buoyant oceanic crust began to subduct (Lonsdale, 1991). The plate motion vector between North America and the subducting Guadalupe and Magdalena microplates then changed from subduction to oblique convergence to dextral transform motion. This change initiated strike-slip motion along the Tosco-Abreojos fault located along the western edge of Baja California (Fig. 3D). Once spreading ceased altogether at about anomaly 5A time (ca. 12 Ma) (Lonsdale, 1991) and both the Guadalupe and Magdalena microplates were captured by the Pacific plate, transtensional Pacific plate motion relative to North America was then partitioned into strike-slip motion along the Tosco-Abreojos fault (and the subduction interface that dipped beneath Baja California) and extension within the nascent Gulf of California. In the process, Baja California rotated clockwise ~10° as it rifted and translated away from North America (Fig. 3, D and E). This model of microplate capture predicts that initial extension in the Gulf of California occurred at about 12–14 Ma (Stock and Hodges, 1989), when Guadalupe and Magdalena spreading first slowed and then eventually stopped. It also predicts that Baja moved nearly 400 km relative to North America, with ~150–160 km of that motion occurring prior to anomaly 3–3A time

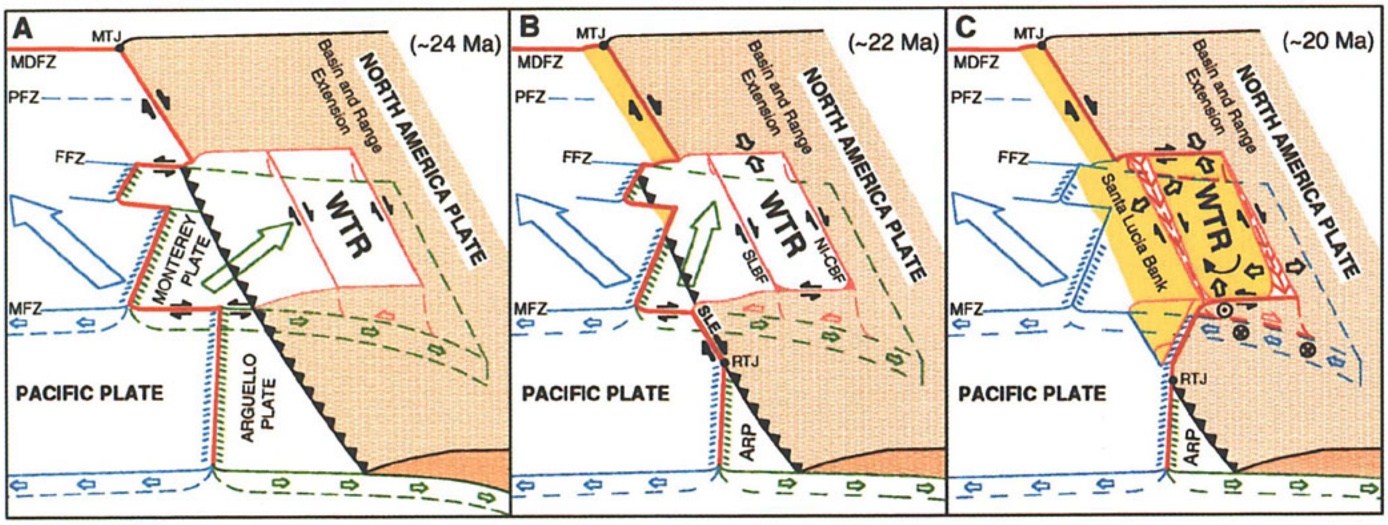
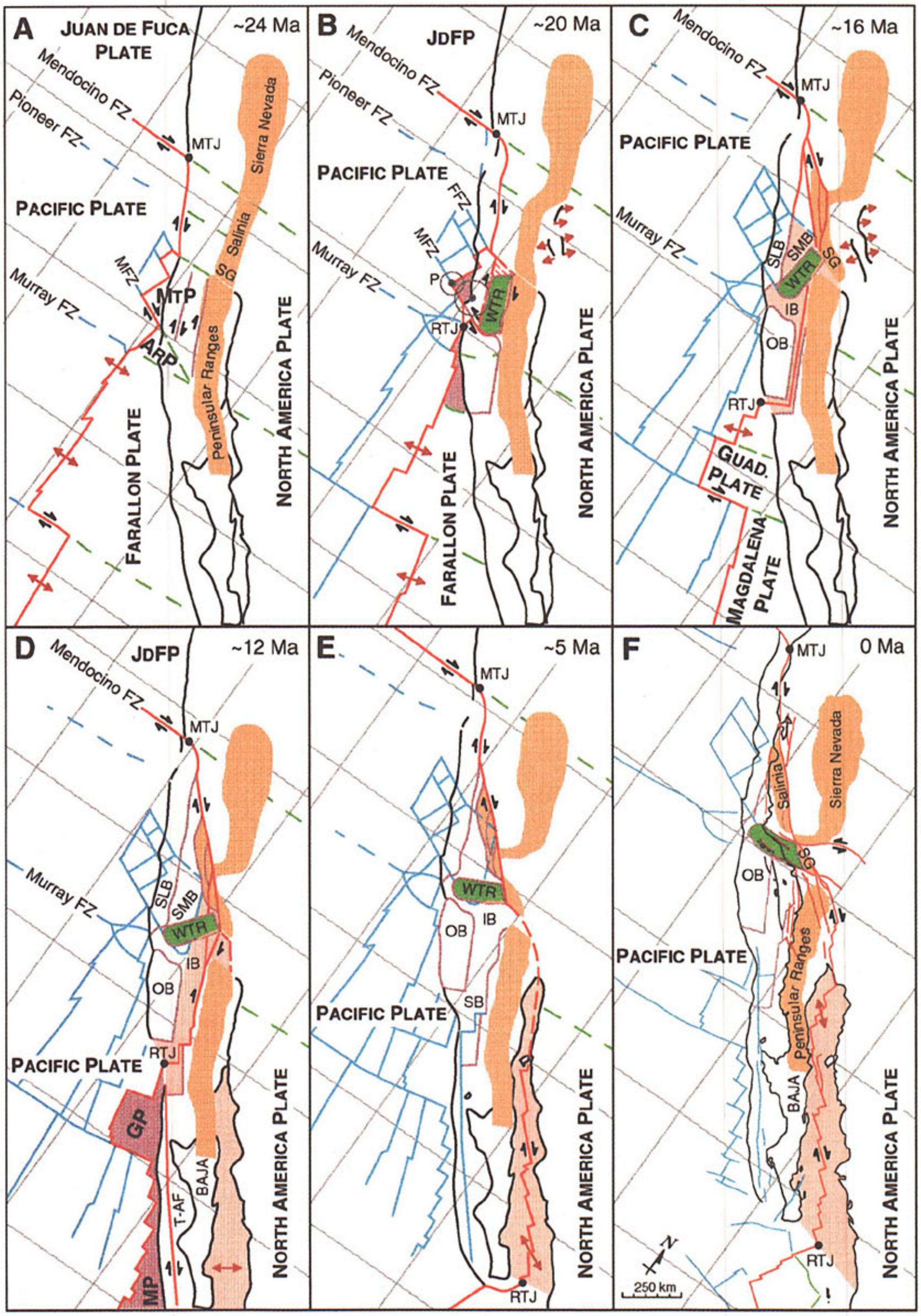


Figure 2. Schematic block diagrams showing capture of partially subducted Monterey microplate by Pacific plate. From 24 to 22 Ma, Monterey subduction slows, causing Monterey–North America plate motion (green) to become more oblique, until it finally assumes Pacific plate motion (blue) at 20 Ma. Yellow—North America crust captured by Pacific plate; red—edge of Pacific plate or areas of extension; FFZ, MFZ, MDFZ, PFZ—Farallon, Morro, Mendocino, and Pioneer fracture zones; MTJ and RTJ—Mendocino and Rivera triple junctions; WTR—western Transverse Ranges block; NI-CBF—Newport-Inglewood–Coronado Bank fault; SLBF—Santa Lucia Bank fault; SLE—tectonically eroded Santa Lucia Escarpment; ArP—Arguello plate.

Figure 3. Simple tectonic model of Pacific–North America plate interactions since 24 Ma. Model assumes constant rate and direction of Pacific plate motion and constant rate of western Transverse Ranges (WTR) rotation. When partially subducted Monterey (20 Ma), Arguello (17.5 Ma), and Guadalupe and Magdalena (12 Ma) microplates are captured, part of North America upper plate is transferred to Pacific plate. Fine gray lines provide reference grid tied to fixed North America; error circles in B are estimated uncertainties in position P from this model and Stock and Molnar (1988). ArP—Arguello plate; GP—Guadalupe plate; MtP—Monterey plate; SG—San Gabriel block; JdFP—Juan de Fuca plate; SLB—Santa Lucia Bank; SMB—Santa Maria basin; IB, OB, SB—inner, outer, and southern borderland, respectively; T-AF—Tosco-Arbreojos fault; MP—Magdalena plate; red areas—regions of transtension; purple areas—captured or soon-to-be captured microplates. See Figure 2 for other abbreviations.



(ca. 5–6 Ma), when the full Pacific–North America plate motion jumped eastward into the Gulf of California (e.g., Lonsdale, 1991).

DISCUSSION

If the tectonic evolution of the California margin were significantly affected by the sequential capture of partially subducted microplates by the Pacific plate, then several important implications follow. First and foremost, the Pacific–North America transform plate boundary began, for the most part, as a low-angle structure that has only gradually evolved in places toward a more vertical strike-slip fault system. The initial transform boundary rarely occupied the original edge of the continental margin (i.e., the paleotrench), but rather extended inland down-dip along the subduction interface. The exceptions would be the Santa Lucia Escarpment (south of the Morro fracture zone), which was active from about 22 to 19 Ma, and north of the Pioneer fracture zone, where much of the transform plate motion has been localized since about 28 Ma. South of the Farallon fracture zone, subducted oceanic crust captured by the Pacific plate now extends under much of the continental margin at least as far east as the present San Andreas fault and the Gulf of California. This overlap is possible because, when this crust was subducted, it was not Pacific plate, but remnant pieces of the subducting Farallon plate. Capture of this subducted plate by the Pacific plate subjected the overriding continental material to distributed transtensional transform motion. Depending on block size, geometry, and boundary conditions, this motion produced either rotation and translation (e.g., the western Transverse Ranges), transtensional rifting and translation (e.g., the outer borderland), or the partitioning of strain into nearly pure strike-slip motion and crustal extension (e.g., Baja California). Total displacement since anomaly 6 time (ca. 20 Ma) of the captured Monterey plate relative to presumed fixed North America is about 820 ±50 km. This agrees closely with global plate circuit estimates of about 875 ±75 km (Stock and Molnar, 1988) for the same time period (Fig. 3B).

Of equal importance is the recognition of what may happen as a spreading ridge approaches a trench and young oceanic crust begins to subduct. As the buoyancy of young, hot material begins to compensate for slab pull, subduction and spreading may slow and the coupling between the two spreading plates may increase. This can happen if the entire subducting plate is itself relatively young, if the subducting plate is small, or if the subducting plate has become detached from the older, colder, sinking slab. The net result is that when subduction and spreading cease, the two originally spreading plates become effectively one, and the previously subducting slab now takes on the motion of the plate that captures it. This transfer or capture of young subducting slabs may occur before or after the spreading ridge has reached the trench, and may provide an effective mechanism for the transfer of continental crust from one plate to another, as well as a reasonable explanation for how subduction zones evolve into transform regions, or areas of crustal extension.

CONCLUSIONS

The observation of partially subducted Monterey plate beneath the central California margin and the coincidence in timing of initial rotation of the western Transverse Ranges with the transfer of the Monterey plate to the Pacific plate in early Miocene time suggest a direct cause and effect. Once the Monterey plate joined the Pacific plate, a substantial piece of oceanic crust subducted beneath the western edge of North America was now moving with Pacific plate motion. This implies that the initial geometry of the San Andreas transform fault system was a nested family of faults that soled into a basal decollement that coincided with the top of subducted oceanic crust. This model of microplate capture accounts for several previously difficult or unexplained phenomena, including the apparent overlap of the Pacific and North America plates, rotation of the western Transverse Ranges, the appearance of strike-slip motion well inland of the margin in early Miocene time, large-scale extension and transtensional rifting in the inner and southern borderland regions, the presence of low-angle detachments under much of central and southern California, and the initial rifting of Baja California at about 12–14 Ma. Even the movement of Salinia may be understood in the context of this model, although that is beyond the scope of this paper. The model may also explain the apparent paradox of a broad heat-flow anomaly over the San Andreas fault system (Lachenbruch and Sass, 1992), because in this case the transform originated as a family of widely distributed strike-slip faults that flattened into a basal shear surface, parts of which may still be active today. Given the extent to which the Pacific plate has successfully captured remnant pieces of the subducted Farallon plate, we thus expect that this process of microplate capture is largely responsible for much of the tectonic evolution of the California continental margin.

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