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Reconstructing southern California

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ABSTRACT

Southern California is a critical component in paleotectonic models for: (1) the evolution of the USA-Mexico Cordillera, (2) the interaction of continental and oceanic plates, and (3) relations between subduction and transform processes during the Mesozoic and Cenozoic. Detailed palinspastic reconstruction of both offshore and onshore components of the diverse and complex settings of southern California is essential in order to test paleotectonic models for the evolution of the broader region. The unique geologic history of southern California can be described in terms of distinct phases of tectonic development, which resulted in corresponding distinct tectonostratigraphic sequences. Steep-slab subduction of the Farallon plate characterized most of the Cretaceous history of the southwestern USA, whereas flat-slab subduction characterized the Laramide orogenic event (80-40 Ma). As the subducting Farallon plate rolled back following the Laramide orogeny, the Pacific plate first came into contact with the North American plate in southern California soon after 30 Ma. Two triple junctions then traveled in opposite directions along the continental margin. The southern triple junction had a complex history, including three distinct stages of capture of Farallon microplates and contiguous parts of the North American margin by the Pacific plate. These three microplate-capture events resulted in transrotation (18-12 Ma), transtension (12-6) and transpression (6-0 Ma) in the Los Angeles region. Reconstructing this complex history is an extraordinarily challenging and rewarding endeavor.

INTRODUCTION

The geologic history of southern California (Fig. 1) is unlike the known history of any other location on Earth. Relatively typical steep-slab subduction of the Farallon plate characterized most of the Cretaceous history of the southwestern USA (Fig. 2; Dickinson, 1981; Ingersoll, 1997), whereas flat-slab subduction characterized the Laramide orogenic event (80-40 Ma) (Dickinson and Snyder, 1978; Bird, 1984, 1988). As the subducting Farallon plate rolled back following the Laramide orogeny, the Pacific plate first came into contact with the North American plate in southern California soon after 30 Ma (Atwater, 1970, 1989; Bohannon and Parsons, 1995). Two triple junctions then traveled in opposite directions along the continental margin (Dickinson and Snyder, 1979). The southern triple junction had a complex history, including three distinct stages of capture of Farallon microplates and contiguous parts of the North American margin by the Pacific plate (Nicholson et al., 1994). These three microplate-capture events resulted in transrotation (18-12 Ma), transtension (12-6) and transpression (6-0 Ma) in the Los Angeles region (Fig. 1) (Ingersoll and Rumelhart, 1999). These events induced complex responses in adjacent areas. Reconstructing this complex history is an extraordinarily challenging endeavor; the present contribution outlines recent progress in our understanding and points toward possible future work. It would be interesting to discover if any other ancient complex continental margins have experienced similar events.

Rigorous paleotectonic reconstruction of southern California (Fig. 1) is critical for testing diverse types of models: (1) Truncation of Paleozoic and Mesozoic continental-margin trends (e.g., Fig. 2); (2) Location, sense and magnitude of slip

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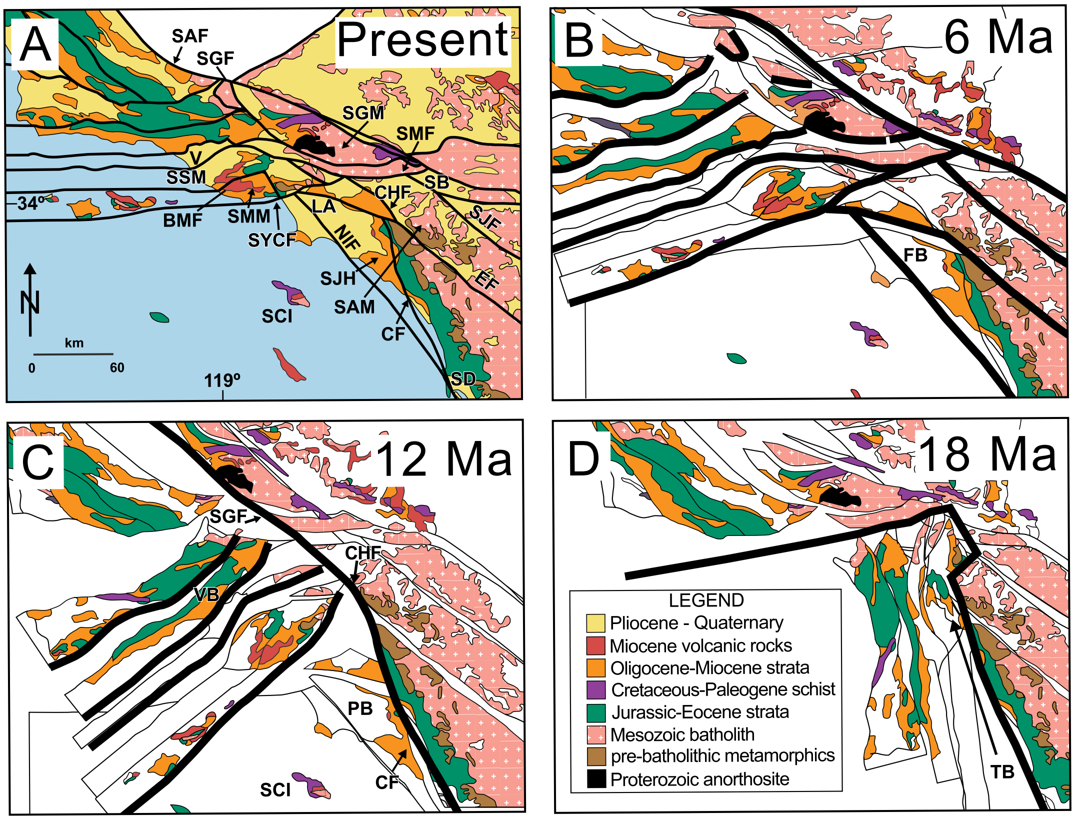


Figure 1. Present and palinspastic geologic maps of Los Angeles area. Legend in D is for A-D. In B-D, light lines (some of which are known or suspected faults) separate blocks used in palinspastic reconstruction; heavy lines are presumed active faults. See Ingersoll and Rumelhart (1999) for detailed caption. See Figure 2 for location.

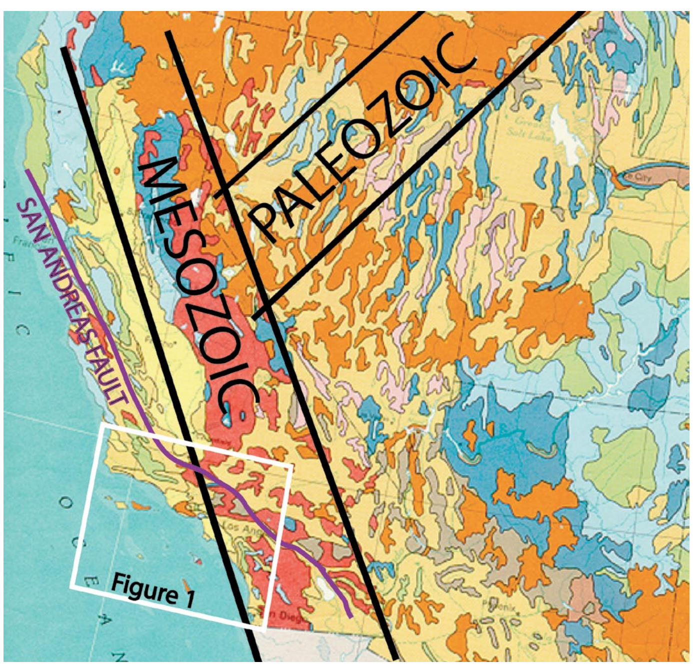


Figure 2. General geologic map of southwestern USA showing truncation of NE-SW Paleozoic continental-margin trends (e.g., Antler and Sonoma) by both Mesozoic and Cenozoic NW-SE continental-margin trends. Also, note that late Cenozoic trends (e.g., San Andreas fault) cut obliquely across Mesozoic trends, with wider parts of the North American continental margin having been captured by the Pacific plate to the south.

of transform faults of diverse ages near the continental margin (e.g., Anderson and Schmidt, 1983; Dickinson, 1983; Powell and Weldon, 1992; Dickinson and Lawton, 2001); (3) Reconstruction of Mesozoic arc-trench systems (including sutures, arcs, backarcs, forearc basins and subduction complexes) (e.g., Schweickert and Cowan, 1975; Ingersoll and Schweickert, 1986; Hall, 1991; Ingersoll, 1997; Moores, 1998; Dickinson and Lawton, 2001; Grove et al., 2003; Saleeby, 2003); and (4) Locations of Mesozoic-Cenozoic oceanic-plate boundaries along the continental margin (e.g., Nicholson et al., 1994; Bohannon and Parsons, 1995; Atwater and Stock, 1998).

TECTONOSTRATIGRAPHY

Stratigraphic units of southern California may be placed within tectonostratigraphic sequences that correspond with distinct phases of tectonic development of the area (Fig. 3; Ingersoll and Rumelhart, 1999; Ingersoll, 2001). The following events must be understood and their effects must be removed in order to achieve the desired reconstruction backward through time: Late Jurassic "Nevadan" orogeny, followed by initiation of Cretaceous Franciscan-Great Valley-Sierran arc-trench system (and slightly younger southern California equivalents); Cretaceous "normal" subduction (120-80 Ma), followed by Laramide flat-slab subduction of Farallon plate (80-40 Ma); rapid rollback of slab and return of magmatic arc to its "normal" position (40-30 Ma); initiation of

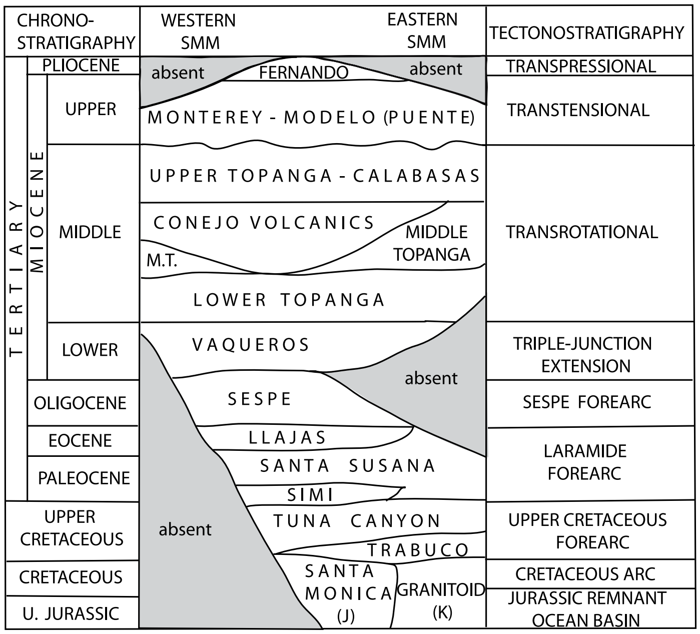


Figure 3. Stratigraphy of Santa Monica Mountains. Chronostratigraphy and tectonostratigraphy are indicated on left and right, respectively. In center are stratigraphic names. Modified after Dibblee (1992a) (from Ingersoll, 2001).

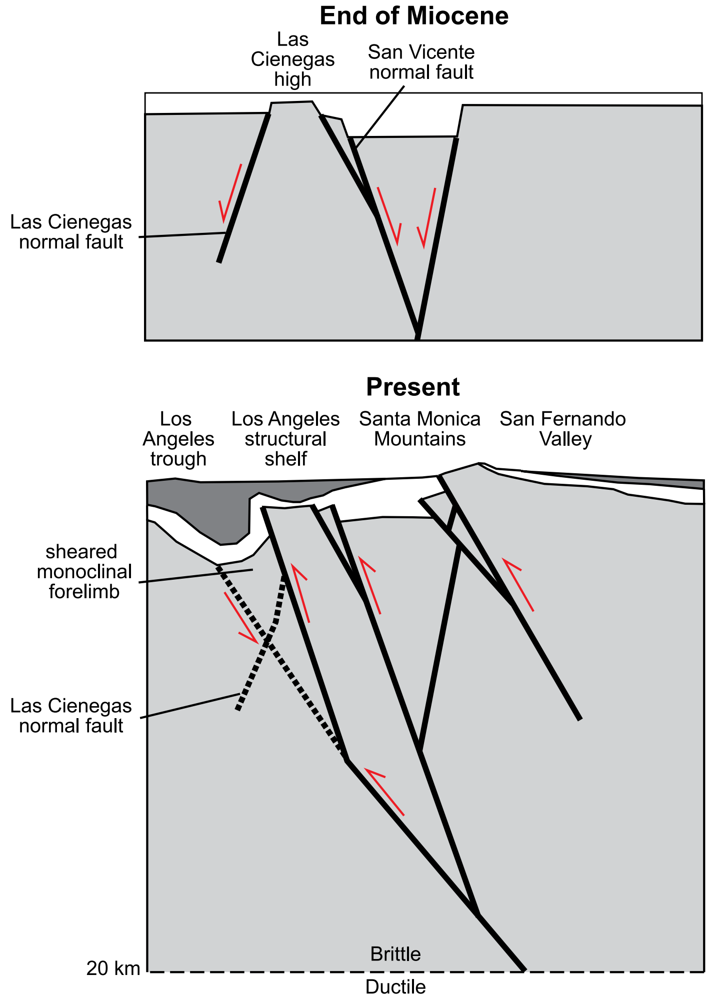


Figure 4. Schematic cross sections showing active transpressional shortening along fault zones that were transtensional normal-fault zones approximately 12-6 Ma. Light gray indicates Mesozoic metamorphic and plutonic basement. White stratigraphic interval represents transtensional growth strata (12-6 Ma); dark-gray interval represents transpressional growth strata (6-0 Ma). Upper figure shows end of Miocene reconstruction of boundary between Los Angeles basin (left, south) and San Fernando Valley (right, north). Lower figure shows present cross section with same orientation, showing uplift of Santa Monica Mountains along a reverse fault. See figures 1, 5 and 7 for locations of Los Angeles and Santa Monica Mountains. Figure 7 shows approximate location of cross sections. Modified from Schneider et al. (1996).

Pacific-North American plate interaction (soon after 30 Ma), followed by NW movement of the unstable Mendocino triple junction and SE jumping of the Rivera triple junction during three microplate captures, resulting ultimately in the transfer of Baja and coastal southern California to the Pacific plate. These paleotectonic events are represented by the following tectonostratigraphic units in the Santa Monica Mountains and vicinity (Fig. 3): Jurassic "Nevadan" orogeny (Santa Monica and Bedford Canyon Fms.), Cretaceous forearc (Tuna Canyon and Chatsworth Fms.), Laramide forearc (Santa Susana and San Francisquito Fms.), transitional forearc (Sespe Fm.), triple-junction extension (Vaqueros and Vasquez Fms.), transrotation (Topanga Fm.), transtension (Modelo and Puente Fms.) and transpression (Fernando Fm.). Systematic retrodeformation of each event (using all available data sets), from youngest to oldest, should provide important constraints for paleotectonic models.

TRANSPRESSIONAL TECTONICS (6-0 MA)

The youngest phase of deformation began with transfer of Baja California to the Pacific plate and initiation of the modern southern San Andreas fault (Nicholson et al., 1994; Axen and Fletcher, 1998; Ingersoll and Rumelhart, 1999; Oskin et al., 2001; Oskin and Stock, 2003). The major restraining bend in the San Andreas fault system through the Transverse Ranges has been accommodated along numerous reverse and thrust faults, with associated flexural foreland basins (Fig. 4), and rapid uplift, erosion and deposition; structural inversion of former normal faults (from transtensional phase) have resulted along many reverse-fault zones (e.g., Yeats, 1987; Dibblee, 1992b; Yeats et al., 1994; Schneider et al., 1996). The Fernando Formation of the Los Angeles basin area represents the tectonostratigraphy of this phase (Fig. 3).

TRANSTENSIONAL TECTONICS (12-6 MA)

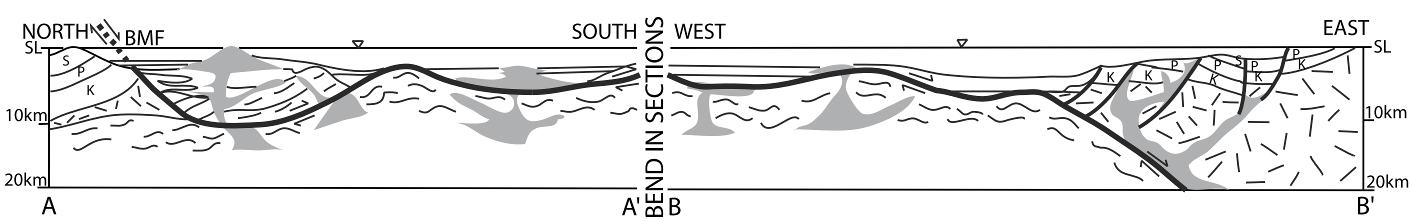
Capture by the Pacific plate of the Guadalupe and Magdalena microplates at 12 Ma (Nicholson et al., 1994) initiated slip along the combined San Gabriel (Canton) - Chino Hills

- Christianitos - Tosco - Abreojos fault system (Crowell, 1952, 2003; Spencer and Normark, 1979; Ingersoll and Rumelhart, 1999). The southern part of this fault system (T-A) was located along the Baja continental margin; a right step in the right-slip system occurred where the C-CH faults cut inboard to link with the SG(C) system (Fig. 1). This resulted in a releasing bend, so that transtensional faulting caused rapid subsidence, stretching and heating of the Los Angeles basin, within which the Puente and Modelo submarine fans were deposited (Wright, 1991; Critelli et al., 1995; Rumelhart and Ingersoll, 1997). The Puente Formation of the Los Angeles basin area represents the tectonostratigraphy of this phase (Fig. 3).

TRANSROTATIONAL TECTONICS (18-12 MA)

Capture by the Pacific plate of the Monterey and Arguello microplates between 20 and 17 Ma (Nicholson et al., 1994) initiated transrotation of the Western Transverse Ranges (WTR) block (Luyendyk, and Hornafius, 1987; Luyendyk, 1991; Dickinson, 1996; Ingersoll and Rumelhart, 1999). Crouch and Suppe (1993) illustrated how transrotation of the WTR was accompanied by exhumation of the Mesozoic-Paleogene subduction complex, which now underlies much of the continental borderland and is exposed on Catalina Island (Fig. 5). In the process of transrotation, segments of the forearc crust were highly extended, to the point of lithospheric rupture; transitional oceanic crust resulted, where asthenospheric melts intruded bathyal turbidites of the same age (Fig. 6). Breakaway

Figure 6. View to the northeast, showing road cut through north-dipping bathyal turbidites of the lower Topanga Formation (Middle Miocene), intruded by north-tilted (originally subvertical) basaltic dikes of the Conejo Volcanics (also Middle Miocene) at Point Mugu (see Fig. 7 for location). Lettering "bathyal turbidites" is parallel to trace of sedimentary bedding. Rapid sedimentation, rapid lithospheric extension and voluminous asthenospheric decompression magmatism were concurrent; this is one of the few examples on Earth of exposed transitional oceanic crust. See Dibblee (1990) for details at this locality.



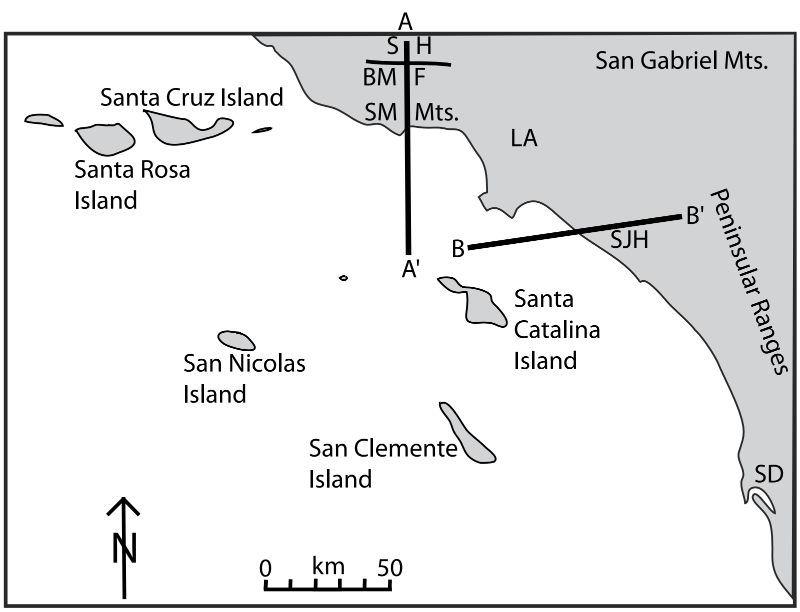


Figure 5. Transrotation of the Western Transverse Ranges and exhumation of the Catalina Schist to form the continental borderland. Detachment fault is the exhumed subduction zone under the Peninsular Ranges, as shown on the upper right. It comes to the surface as a breakaway zone within the Santa Monica Mountains (BMF=Boney Mountain fault). K=Cretaceous. LA=Los Angeles. P=Paleogene undifferentiated. S=Oligocene Sespe Formation. SD=San Diego. SH=Simi Hills. SJH=San Joaquin Hills. SM Mts.=Santa Monica Mountains. Unlabelled strata are Middle Miocene and younger, interfingering with volcanic and hypabyssal rocks shown in gray. Squiggles represent Catalina Schist. Laths indicate Mesozoic plutonic and related metamorphic rocks. (Modified from Crouch and Suppe, 1993).

zones (i.e., Spencer, 1984; Wernicke and Axen, 1988) linked by transfer zones, which separated unextended from highly extended blocks, developed during transrotational extension (Fig. 7). The oldest strata containing clasts of Pelona-Orocopia Schist were deposited during this period (e.g., Ingersoll and Colasanti, 2004; Colasanti and Ingersoll, 2006), generally in the vicinity of the northeast corner of the rotating WTR; crustal extension related to initiation of transrotation seems to have finally exhumed the Pelona-Orocopia Schist following a complex Cretaceous-Paleogene thermotectonic history (e.g., Grove et al., 2003; Jacobson et al., 2007). The Topanga Formation of the Los Angeles basin area represents the tectonostratigraphy of this phase (Fig. 3). Fritsche et al. (2001) demonstrated numerous stratigraphic and sedimentologic sim-

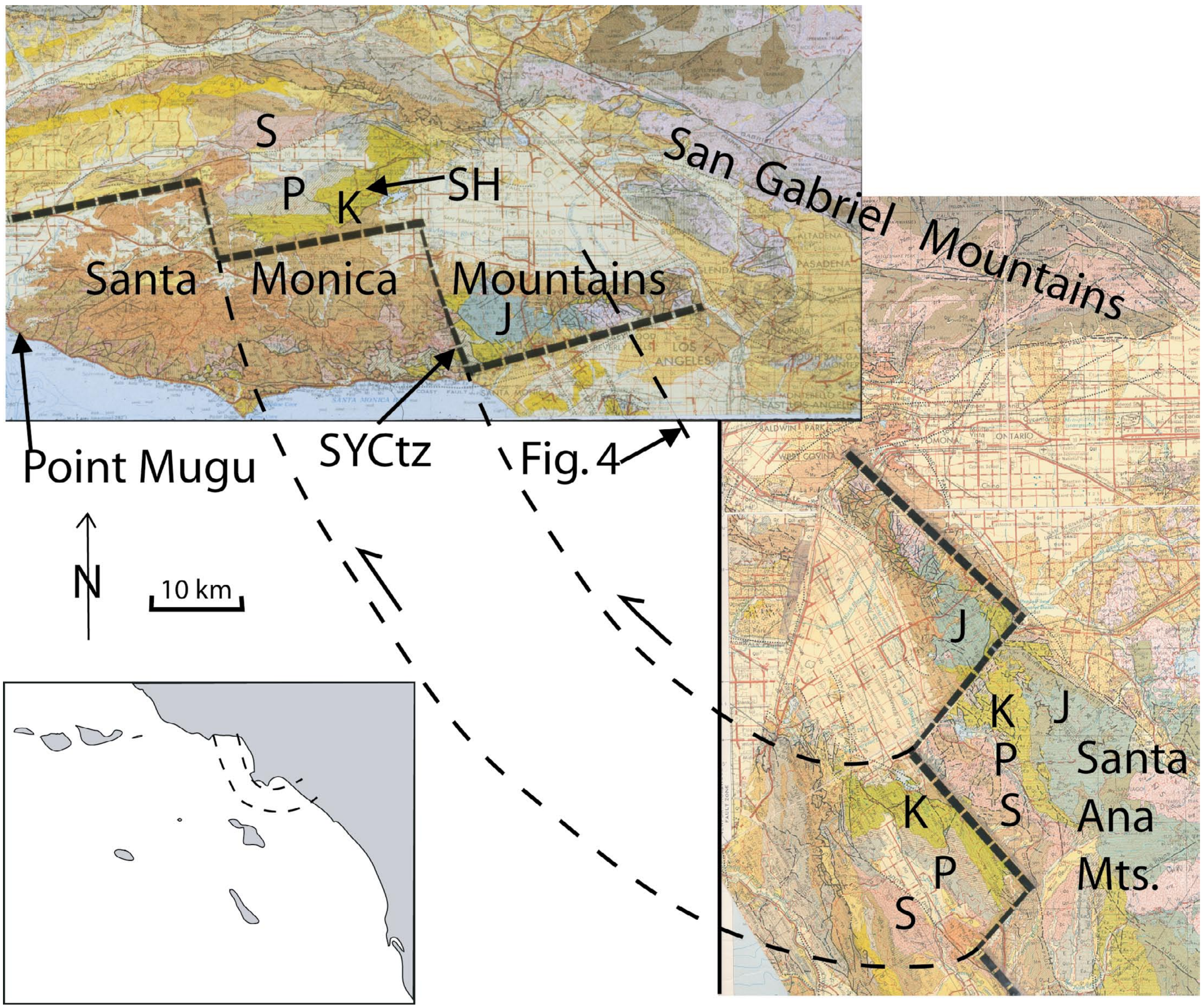


Figure 7. Geologic maps of Santa Monica Mountains (SMM), Santa Ana Mountains, San Gabriel Mountains and adjoining areas (originals at 1:250,000), showing inferred breakaway and transfer zones (simpler version shown in Figure 1D) that accommodated transrotation of Western Transverse Ranges away from the Peninsular Ranges, resulting in cross sections shown in Figure 5. The north end of cross section A-A' of Figure 5 is near the K in the Simi Hills in Figure 7. South of the Boney Mountain fault (breakaway zone), the SMM consist of highly extended terrane, including abundant volcanic and hypabyssal rocks. Extension is greatest at the western end of the SMM, at Point Mugu (Fig. 6). Crust north of the breakaway zones, such as the eastern SMM, is unextended. Oligocene strata (Sespe Formation) was eroded from the eastern SMM during footwall uplift during transrotation. Clasts from the Sespe are abundant in the Middle Miocene Topanga Formation in the central SMM, west of the Santa Ynez Canyon transfer zone (SYCtz). J=Jurassic metasedimentary strata; K=Cretaceous; P=Paleogene undifferentiated; S=Oligocene Sespe Formation. All stratigraphic units in Simi Hills (north of SMM in modern orientation) are thicker, more distal and/or deposited in deeper water than their adjoining strata in Santa Ana Mountains when restored to their pre-Miocene positions (lower right). Location map in lower left is same as in Figure 5.

ilarities between the Santa Monica Mountains and the Santa Ana Mountains in support of the reconstruction shown in figures 1 and 7.

TRIPLE-JUNCTION EXTENSION (24-18 MA)

The Pacific plate first came into contact with the North American plate soon after 30 Ma (Atwater, 1970, 1989; Bohannon and Parsons, 1995). Two triple junctions migrated in opposite directions along the coast as the new transform boundary lengthened; the northern Mendocino triple junction has had an unstable configuration throughout its history (Dickinson and Snyder, 1979), resulting in regional extension in adjoining parts of North America (Ingersoll, 1982b). This regional extension was expressed as core complexes of the Mojave Desert region (e.g., Glazner and Bartley, 1984; Ingersoll et al., 1996; Glazner et al., 2002) and half-graben sedimentation throughout coastal southern and central California (e.g., Bohannon, 1975; Hendrix and Ingersoll, 1987; Tennyson, 1989; Cole and Stanley, 1995; Law et al., 2001). These half grabens have been dispersed along the coast by subsequent transform motion. The Simmler, Plush Ranch, Vasquez and Diligencia formations represent the tectonostratigraphy of this phase. Marine strata of the same age are generally referred to as the Vaqueros Formation (Fig. 3).

SESPE FOREARC (40-24 MA)

Following the end of Laramide flat-slab subduction (80-40 Ma; Dickinson and Snyder, 1978; Bird, 1984, 1988), fluvial-alluvial sedimentation resulted in deposition of the mostly Oligocene Sespe Formation in the forearc of southern California (Nilsen, 1987; Howard, 2000, 2006). The Sespe Formation accumulated in a north-south trough, bounded on the west by the Franciscan-Catalina subduction complex and on the east by the roots of the mostly Cretaceous magmatic arc, and interfingering southward with marine deposits. Clast types and regional reconstructions suggest primarily distant sources for sediment, including paleo-Amargosa and paleo-Gila drainages (Howard, 2000, 2006). Exposures of Sespe Formation are widely dispersed, but they reconstruct to a fairly compact area. The absence of Sespe strata in local areas, such as the eastern Santa Monica Mountains (Fig. 3) indicates that this part of the Santa Monica Mountains was a footwall uplift north of the breakaway zone during transrotational rifting (Figs. 1 and 7).

LARAMIDE FOREARC (80-40 MA)

The convergence rate between North America and the Farallon plate increased at approximately 80 Ma (Coney, 1976; Engebretson et al., 1985), which when combined with attempted subduction of buoyant oceanic crust (Livaccari et al., 1981), resulted in the classic Laramide orogeny (Dickinson and Snyder, 1978; Bird, 1984, 1988; Ingersoll, 1997). Many dispersed stratigraphic sequences represent this period in southern California (Fig. 3); these units represent deep-marine, shallow-marine and nonmarine deposits (e.g., Dickinson, 1995a). During flat-slab subduction, southern California was a very broad forearc, with rivers transporting sediment long distances from the east (Nilsen, 1987; Abbott and Smith, 1989). As the magmatic arc migrated east, drainage systems lengthened and brought increasingly distal sediment to the coast, where it was deposited in forearc basins or in the trench; the latter deposits were underplated to form the Rand-Pelona-Orocopia schists, which have subsequently been uplifted and exposed (Grove et al., 2003; Jacobson et al., 2007). In contrast with the Great Valley forearc to the northwest (e.g., Ingersoll, 1982a) or the Peninsular forearc to the southeast (e.g., Busby-Spera and Boles, 1986), the Salinian and Mojave forearc consisted of complex disrupted continental and transitional crust, due to either Laramide sinistral truncation (e.g., Dickinson, 1983; Dickinson et al., 2005) or Laramide shortening (e.g., Hall, 1991; Saleeby, 2003). The Maniobra Formation (Advocate et al., 1988), San Francisquito Formation (Kooser, 1982), and diverse strata of Salinia (Grove, 1993) were deposited in complex, locally fault-controlled basins on disrupted magmatic-arc basement.

CRETACEOUS FOREARC AND MAGMATIC ARC (120-80 MA)

Only small remnants of the Cretaceous forearc basin and subduction complex are preserved on land in southern California. Cretaceous strata as old as Turonian (ca. 90 Ma) exposed along the west side of the Santa Ana Mountains represent the eastern edge of the forearc basin. These strata were deposited in nonmarine, shallow-marine and slope environments (Bottjer et al., 1982). Thicker submarine-fan deposits are found in the WTR (Link et al., 1981); these submarine-fan deposits restore to the west side of the Santa Ana Mountains when transrotation is removed (Figs. 1 and 7). By analogy with the Great Valley forearc basin, the Peninsular forearc basin onlapped the eroded roots of the eastward migrating magmatic arc (e.g., Ortega-Rivera, 2003), and concurrently broadened westward by onlap onto the Franciscan/Catalina subduction complex (e.g., Ingersoll, 1982a; Dickinson, 1995b). Details of Cretaceous forearc evolution, mid-Cretaceous strike-slip deformation (e.g., Dickinson, 1983), and Early Cretaceous suturing (e.g., Moores, 1998; Dickinson and Lawton, 2001) await complete palinspastic reconstruction of southern California.

CONCLUSIONS

1. Paleotectonic and paleogeographic reconstruction of southern California is extraordinarily complex.
2. Rigorous systematic reconstruction backward through time is essential to address long-standing regional problems.
3. Diverse data sets must be used to iteratively test sequential reconstructions.

4. Either southern California has experienced unique plate-tectonic interactions, or it might be a well studied analog for other ancient settings.

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