Three-stage evolution of the Los Angeles basin, southern California

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ABSTRACT

We propose that an episode of transtension dominated development of the Los Angeles basin area from 12 to 6 Ma, following middle Miocene transrotation and prior to the modern transpressional regime. Transtension resulted from the releasing bend of the San Gabriel–Chino Hills–Cristianitos fault, which acted as the primary transform boundary in southern California during this episode. Such an interpretation implies that significant transform motion did not occur on the southern San Andreas fault prior to 6 Ma and that the Gulf of California has opened primarily since 6 Ma. We propose a three-stage model for evolution of the Los Angeles basin and vicinity within the evolving transform-fault system: transrotation (18–12 Ma), transtension (12–6 Ma), and transpression (6–0 Ma). Timing of these stages correlates with microplate-capture events, which occurred during conversion from a convergent margin to a transform margin.

INTRODUCTION

The San Andreas fault system, bounding the North American and Pacific plates, dominates the present tectonics of California (Atwater, 1970, 1989). Detailed knowledge of neotectonic events is critical for understanding seismic hazards in active settings such as the Los Angeles area (Fig. 1A) (e.g., Dolan et al., 1997; Yeats et al., 1997). Less obvious is the importance of precursor events (paleotectonics) in creating the three-dimensional architecture of the surface and subsurface, within which recent events are expressed.

Intense study of neotectonics has resulted in detailed models for the kinematics of active fault systems in southern California (e.g., Bird and Rosenstock, 1984; Weldon and Humphreys, 1986; Davis et al., 1989; Shaw and Suppe, 1996; Walls et al., 1998). Extrapolation of neotectonic transpressional fault motions is possible for the past 5 or 6 m.y. (i.e., to the early Pliocene), but with increasing uncertainty with age.

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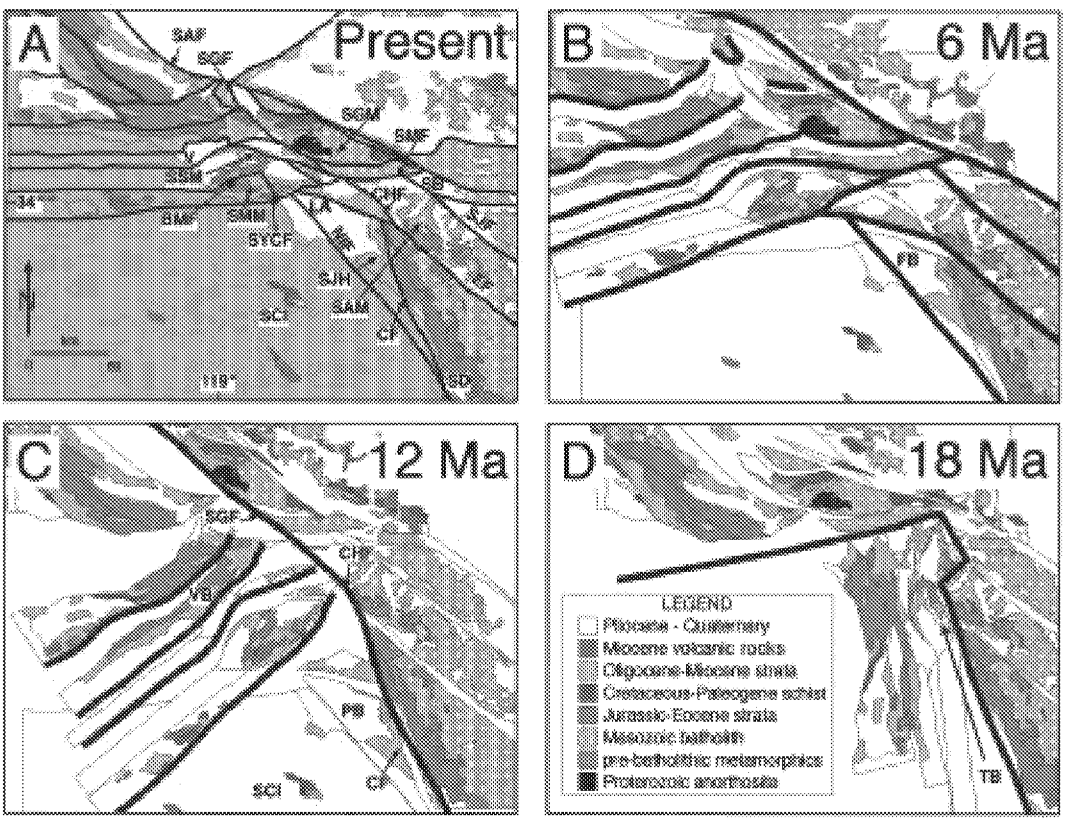

Figure 1. Present and palinspastic geologic maps of Los Angeles area. Legend in D is for A–D. In B–D, light lines separate blocks used in palinspastic reconstruction; some of these boundaries are known faults and others are suspected faults. A: Geologic map of Los Angeles area (after Jennings, 1977). BMF—Boney Mountain fault, CF—Cristianitos fault, CHF—Chino Hills fault, EF—Elsinore fault, LA—Los Angeles, NIF—Newport-Inglewood fault, SAF—San Andreas fault, SAM—Santa Ana Mountains, SB—San Bernardino, SCI—Santa Catalina Island, SD—San Diego, SGF—San Gabriel fault, SGM—San Gabriel Mountains, SJF—San Jacinto fault, SJH—San Joaquin Hills, SMF—Sierra Madre fault, SMM—Santa Monica Mountains, SSM—Santa Susana Mountains, SYCF—Santa Ynez Canyon fault, V—Ventura. B: Palinspastic reconstruction at 6 Ma (see Table 1 for primary constraints). Sinistral and contractional movements have been reversed on several east-west faults, with few constraints. Contractional deformation resulting from left steps of San Andreas fault has been distributed throughout western Transverse Ranges. White areas between fine and heavy lines represent areas covered either tectonically or depositionally since 6 Ma, and heavy lines are faults active between 6 Ma and present. Overlaps of blocks of A represent areas of 6–0 Ma extension, primarily along southern San Andreas fault. FB: Initial transpressional Fernando basin. C: Palinspastic reconstruction at 12 Ma, based on 60 km of dextral slip on San Gabriel fault, which is shown as continuous with Chino Hills and Cristianitos faults. Right step of San Gabriel–Chino Hills–Cristianitos faults east of Puente basin (PB) will result in 12–6 Ma transtension; slight left step of San Gabriel fault north of future Ventura basin (VB) will result in contraction to form Ridge basin (RB) (Crowell and Link, 1982). D: Palinspastic reconstruction at 18 Ma, based primarily on 110° of clockwise rotation of western Transverse Ranges (Luyendyk and Hornafius, 1987; Luyendyk, 1991; Crouch and Suppe, 1993; Nicholson et al., 1994); eastern Santa Monica Mountains area is northeast corner of western Transverse Ranges prior to rotation. Heavy lines show boundaries of western Transverse Ranges microplate prior to rotation (Crouch and Suppe, 1993; Nicholson et al., 1994). Fault boundary between western Transverse Ranges and Santa Ana Mountains is breakaway zone for low-angle detachment, along which Catalina Schist surfaced from under Santa Ana Mountains during transrotation (Crouch and Suppe, 1993). Most volcanism occurred along this breakaway zone. Future Topanga basin (TB) will form as supradetachment basin or basins near evolving breakaway zone.

The recognition of significant vertical-axis clockwise rotation of the western Transverse Ranges and some adjacent areas has stimulated the development of geometric models for fault motions and basin development during transrotation of major parts of southern California (e.g., Luyendyk and Hornafius, 1987; Luyendyk, 1991; Dickinson, 1996). These models predict the overall contribution of transrotational shear to relative plate motions, and they explain observed paleomagnetic data. However, these models fail to predict the location and character of the Los Angeles basin and are geologically oversimplified. Luyendyk (1991) preferred to interpret paleomagnetic data as indicating a constant rotation rate from 18 Ma to the present. Nonetheless, the data can also be interpreted as indicating rapid rotation of the entire block from 18 to 12 Ma, with complex local rotations thereafter. The rotations that we interpret at each stage are similar to those of Nicholson et al. (1994) (Fig. 1).

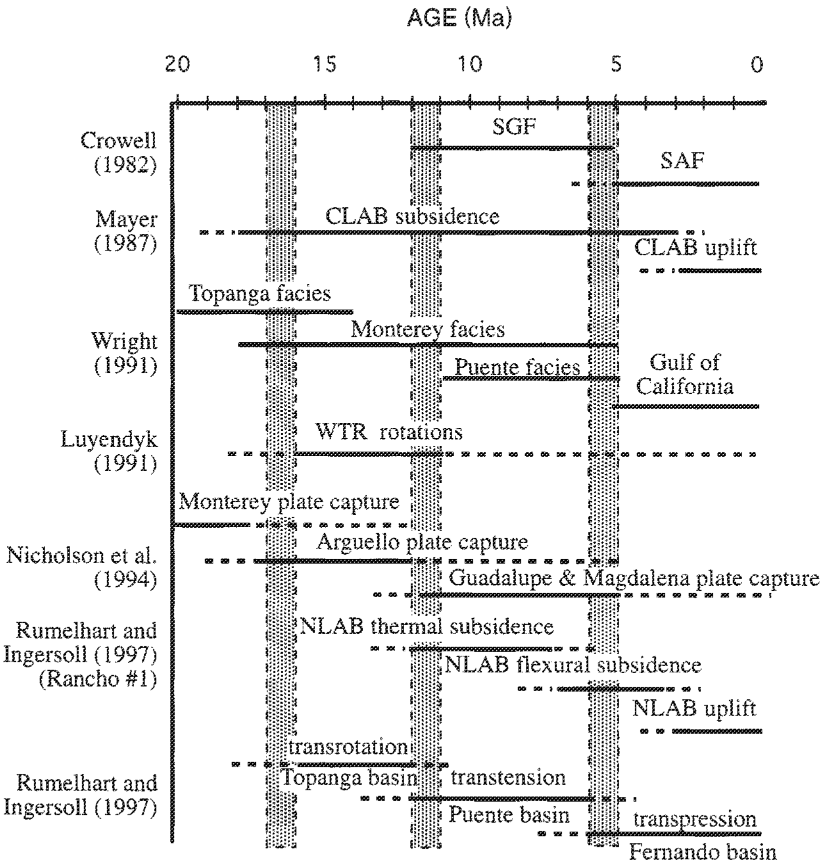

Figure 2. Timing of events discussed in text and literature. Patterned areas indicate times of initiation of three stages of evolution (transrotation, transtension, and transpression), which correspond to deposition of Topanga, Puente, and Fernando Formations, respectively. SGF—San Gabriel fault, SAF—San Andreas fault, CLAB—central Los Angeles basin, WTR—western Transverse Ranges, NLAB—northern Los Angeles basin. Modified from Rumelhart and Ingersoll (1997) and Ingersoll and Rumelhart (1997).

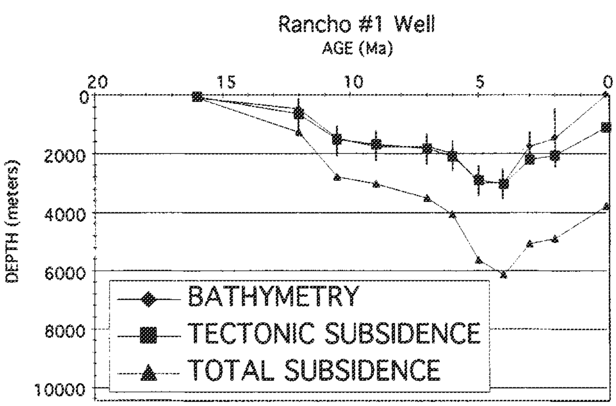

Figure 3. Subsidence analysis of Rancho #1 well from northern Los Angeles basin, showing start of 12 to 6 Ma rapid subsidence (see Fig. 2 and text) and rapid uplift beginning at 4 Ma. Modified from Rumelhart and Ingersoll (1997).

Neither neotectonic transpressional models nor geometric transrotational models explain the observation that the Los Angeles basin area subsided rapidly beginning at ca. 12 Ma. Wright (1991) pointed out that widespread deep-sea fans (e.g., Puente Formation) were deposited from 12 to 6 Ma, a time following rapid rotation and volcanism and preceding north-south contraction in the Los Angeles basin area. This intermediate stage of development is unexplained by existing tectonic models.

We propose a three-stage paleotectonic model for the Los Angeles basin and surrounding areas: transrotation (18–12 Ma), transtension (12–6 Ma), and transpression (6–0 Ma) (Fig. 2) (i.e., Ingersoll, 1988). These stages correlate with microplate-capture events, which occurred during conversion of the California coast from a convergent to a transform margin (Nicholson et al., 1994; Bohannon and Parsons, 1995). Subsidence analysis based on oil-well data (Fig. 3) suggests temporal correlation among microplate-capture events, basin-forming processes, and deposition of tectonostratigraphic sequences (Topanga, Puente, and Fernando Formations, respectively) (Wright, 1991; Rumelhart and Ingersoll, 1997). We discuss each stage in terms of the major basin-filling units—the Topanga, Puente, and Fernando Formations—consistent with the concept of classifying each sedimentary basin on the basis of its tectonic setting during sedimentation (i.e., Ingersoll, 1988).

The principal difference between our model and previous models is the importance attached to the San Gabriel–Chino Hills–Cristianitos fault system as the primary transform plate boundary from 12 to 6 Ma (Fig. 1C). Our model implies little or no strike slip along the present southern San Andreas fault at this time because the San Andreas fault north of the western Transverse Ranges connected with the San Gabriel–Chino Hills–Cristianitos fault, which shunted transform motion offshore of Baja California (Nicholson et al., 1994).

PREVIOUS MODELS

Transpression

The southern San Andreas fault became active at 6 Ma, as Baja California was transferred to the Pacific plate (Nicholson et al., 1994; Axen and Fletcher, 1998). The restraining bend of the San Andreas initiated contraction of the Fernando basin, which rapidly filled with the upward-shallowing Pliocene-Quaternary Capistrano, Fernando, and younger deposits (Wright, 1991). Contraction and rapid uplift have characterized the neotectonics of most of the Los Angeles region, including the Ventura basin. Flexural loading has induced rapid subsidence in front of thrusts and reverse faults (Wright, 1991; Yeats and Beall, 1991; Schneider et al., 1996).

Transrotation

Transrotation occurred during capture of the Monterey and Arguello microplates by the Pacific plate (Nicholson et al., 1994). Paleomagnetic data documenting, on average, 90° of clockwise rotation of the western Transverse Ranges are robust (e.g., Luyendyk and Hornafius, 1987; Luyendyk, 1991), but reconstructions based only on these data suffer from the lack of palinspastic reconstruction of younger events.

Extension along low-angle detachment faults during vertical-axis rotation exhumed middle- and lower-crustal rocks (upper Mesozoic and lower Cenozoic accretionary prism) in the continental borderland (e.g., Santa Catalina Island; Fig. 1C) and formed one or more precursors (herein called the Topanga basin; Fig. 1, C and D) to the modern Los Angeles basin (e.g., Crouch and Suppe, 1993).

Determination of boundaries between highly extended continental crust and transitional oceanic crust is complicated by the cryptic nature of basement beneath the modern Los Angeles basin (Wright, 1991) and by overprinting during later transtensional and transpressional deformation. This basement could be part of the moderately extended upper plate (batholithic) or partially exhumed lower plate (Catalina Schist).

Transtension

Rapid extension created the bathyal Puente basin (Fig. 1C), within which the upper Miocene Tarzana (Modelo) and Puente submarine fans and the Monterey Shale, the primary petroleum source rock of the region, accumulated (Wright, 1991; Critelli et al., 1995; Rumelhart and Ingersoll, 1997). Rapid subsidence of the Puente basin between 12 and 6 Ma coincided with right slip of 60 km along the San Gabriel fault (e.g., Crowell, 1982). There are few constraints on slip history of the Chino Hills or Cristianitos faults, which bounded the Puente basin.

THREE-STAGE MODEL

Our palinspastic model (Fig. 1) was constructed iteratively by reversing known or inferred fault motions from the present back to 18 Ma. Major constraints are summarized in Table 1; additional constraints are indicated in the caption to Figure 1. We present our modifications and additions to existing models in chronological order, opposite to how Figure 1 was constructed.

During transrotation (18–12 Ma), the magnitude of extension decreased toward a pivot point east of the Santa Monica Mountains, so that the middle Miocene Topanga basin deepened to the south and west. Transfer zones separated highly extended areas (e.g., western Santa Monica Mountains) from less extended areas (e.g., eastern Santa Monica Mountains); basaltic magmatism (e.g., Weigand and Savage, 1993; Dickinson, 1997) was concentrated at the edges of highly extended blocks, especially near the breakaway. North of the western Santa Monica Mountains, footwall uplift at the breakaway (possibly the Bony Mountain fault) for the currently south-dipping detachment fault exposed a thick sequence of Cretaceous-Paleogene forearc strata in the Chatsworth and Simi Hills (Yeats, 1983, 1987). No such footwall uplift exists in the area of the San Fernando Valley.

East of the Santa Ynez Canyon fault (or transfer zone, newly named herein; see Dibblee, 1992), the breakaway was along the south side (present orientation) of the eastern Santa Monica Mountains. Footwall uplift here caused erosion of most of the Paleogene section prior to deposition of the Topanga Formation; the only exposed fragment of crystalline basement (Mesozoic Santa Monica Slate and batholithic intrusions) outboard (currently north) of the breakaway is found here. Our reconstruction places this basement block at the north end of the Santa Ana Mountains prior to 18 Ma (Fig. 1, A and D).

Subsidence analysis (Rumelhart and Ingersoll, 1997) indicates that the Puente and Fernando basins subsided most rapidly from 12 to 4 Ma (Fig. 3); in contrast, the Topanga basin subsided most rapidly from 16 to 12 Ma. These observations are consistent with increased rates of sedimentation away from the northeastern pivot of the western Transverse Ranges during transrotation (18–12 Ma), and concentration of younger transtension in the Puente basin, close to the San Gabriel–Chino Hills–Cristianitos fault zone (Fig. 1C).

In our model, the San Gabriel–Chino Hills–Cristianitos fault zone became the primary transform boundary at 12 Ma, with initiation of Guadalupe and Magdalena microplate capture (Fig. 2) (e.g., Nicholson et al., 1994). This fault trend formed a releasing bend separating magmatic-arc basement (Santa Ana Mountains) on the east from a deep basin to the west. Our model predicts that the greatest subsidence of the Puente basin (PB, Fig. 1C) occurred along the eastern, fault-bounded margin of the basin (e.g., Wright, 1991), where basement consisting of either batholithic or accretionary rocks beneath the Puente basin was stretched and intruded.

In contrast, north of the eastern Ventura basin, the San Gabriel fault formed a restraining bend, northeast of which the predominantly nonmarine transpressional Ridge basin developed concurrently with deposition of the Modelo, Puente, and Monterey Formations (Crowell and Link, 1982).

Positive structural inversion (i.e., Williams et al., 1989) has characterized the transition from transtension to transpression in the Ventura and Los Angeles basin areas; such structures are especially well expressed along the southern side of the Ventura basin in the Santa Susana Mountains (Yeats et al., 1994) and the south side of the Santa Monica Mountains (Schneider et al., 1996).

TABLE 1. PRIMARY CONSTRAINTS FOR PALINSPASTIC RECONSTRUCTION OF FIGURE 1

Time	Amount of movement	Source
6 Ma	255 km right slip on San Andreas fault	Dickinson (1996)
	25 km right slip on San Jacinto fault	Dickinson (1996)
	30 km right slip on Elsinore fault	Wright (1991)
	20° clockwise rotation of western Transverse Ranges	Nicholson et al. (1994)
12 Ma	60 km right slip on San Gabriel fault	Crowell (1982)
	30° clockwise rotation of western Transverse Ranges (total of 50°)	Nicholson et al. (1994)
18 Ma	60° clockwise rotation of western Transverse Ranges (total of 110°)	Nicholson et al. (1994)

DISCUSSION

This three-stage model has the following implications.

1. It resolves the general relationship between oceanic microplate interactions along the coast and specific fault zones and basins on land.

2. It demonstrates how a small area along an evolving continental-oceanic transform plate margin can undergo distinctly different stages of structural and basin development without changes in kinematics of major plates. For example, recent refinements of North American–Pacific relative plate circuits indicate that microplate-capture events and their onland consequences occurred independently of changes in relative plate motions (Atwater and Stock, 1998).

3. It provides a framework within which to investigate neotectonics of the area and predicts possible subsurface structure (e.g., Fuis et al., 1996). Seismic risks might be better evaluated with these paleotectonic constraints in mind.

4. It provides a general framework for structural control of basin formation, paleoenvironments of these basins, and timing of subsidence and structural disruption (Wright, 1991). These aspects influence petroleum creation, maturation, migration, and trapping; our model may find application in future exploration of the Los Angeles and Ventura areas, two of the most petroliferous basins on Earth (Biddle, 1991).

5. It provides a framework within which to view the extraordinarily complex local environment of the Los Angeles area. A systematic reconstruction of this tectonically active geologic environment has great educational potential.

Future work will integrate structure, stratigraphy, petrology, and paleoenvironments at a larger scale in order to refine our three-stage model. Improved understanding of the sequential evolution of southern California will constrain neotectonic models applicable in seismic hazard assessment and provide a context within which to understand the geologic history of this complex area.

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