Miocene rifting in the Los Angeles basin: Evidence from the Puente Hills half-graben, volcanic rocks, and P-wave tomography

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ABSTRACT

Formation of the Puente Hills half-graben in the northeastern Los Angeles basin and eruption of the Glendora and El Modeno Volcanics (16–14 Ma) help to define the timing of extension in the basin. Normal faulting on the proto-Whittier fault ca. 14 Ma established the Puente Hills half-graben, in which sedimentary strata accumulated between ca. 14 and 10 Ma and into which diabase sills intruded. North-South contraction began to invert the Puente Hills half-graben ca. 7 Ma, leading to formation of the Puente Hills anticline and the Whittier fault. Our high-resolution three-dimensional P-wave velocity model shows two anomalous higher velocity (6.63 km/s) bodies at depths between 9 and 18 km, which we attribute to dioritic plutons named here for Whittier Narrows and El Modeno. The stocklike Whittier Narrows pluton could have been a source for the Glendora Volcanics and the diabase sills in the Puente Hills half-graben. The sill-shaped El Modeno pluton was a likely source for the El Modeno Volcanics. The northwesterly alignment of the plutons may mark the location of the northeastern Los Angeles basin rift boundary, which is associated with the clockwise rotation of the western Transverse Ranges. Three active faults, the Elysian Park blind thrust, the Puente Hills blind thrust, and the Whittier fault, converge on the Whittier Narrows pluton, which may have played a role in their location and segmentation.

Keywords: El Modeno Volcanics, Glendora Volcanics, Puente Hills, tomography, Whittier fault

NORTHEASTERN LOS ANGELES BASIN

The central Los Angeles basin has been buried to great depths, as seen most spectacularly in the American Petrofina Central C.H. No. 1, which at its total depth had penetrated more than 6 km of Pliocene and younger rocks (Fig. 1). Evidence of what happened during the earlier extensional phase of basin evolution is sparse, but indirect inference about early extension has proved fruitful. Many workers now attribute the establishment of the Los Angeles basin to two processes: (1) clockwise rotation of the western Transverse Ranges (Fig. 1) through more than 90° since ca. 18 Ma (Luyendyck, 1991; Nicholson et al., 1994; Ingersoll and Runnehart, 1999) and (2) the formation of a related (?) regional detachment surface above an underlying metamorphic core complex represented by the Catalina schist (Crouch and Suppe, 1993; Bohannon and Geist, 1998). These bold new concepts provide a framework for attempts at characterizing locally the extension-dominated phase of Los Angeles basin evolution. The northeastern Los Angeles basin (Fig. 1) is an area that is well exposed, has an unusually complete oil-well database, and has a large, well-defined earthquake database. The complementary application of structural, stratigraphic, petrologic, and tomographic analyses allows us to speculate on how Miocene extension developed and how it may be related to active tectonics. Of particular significance is the implication that the relationships between crustal heterogeneities and seismicity may be important in evaluating seismic hazards. Our study exemplifies an approach to resolving the structure of inverted sedimentary basins that may prove generally useful to many workers worldwide.

PUENTE HILLS HALF-GRAaben

Marine turbidite sandstones, mudstones, and hemipelagic shale of the Miocene Puente and the Pliocene Fernando Formations crop out in a triangular area of the northeastern Los Angeles basin in and around the Puente Hills (Fig. 1). The character and distribution of the La Vida Member (Fig. 2) provide evidence of Miocene extension. The La Vida Member is more than 1525 m thick north of the Whittier fault in the Shell Keeler Community 1 well, but <=730 m thick (depth corrected) south of that fault in the Chevron Murphy-Whittier 304 well (Fig. 2). North of the fault, the La Vida Member forms a wedge-shaped body, the thickest part of the wedge marking the area of occurrence of the Diamond Bar sandstone and its interbedded siltstones (Figs. 2 and 3). The wedge's thickness is augmented northward by diabase sills that Durham and Yerkes (1964, p. 224) suggested were intruded along the Whittier fault. Diabase is not known within the La Vida Member south of the fault (Durham and Yerkes, 1964, p. 223; Yerkes, 1972, p. C11) (Figs. 2 and 3).

We have interpreted (Bjorklund and Burke, 2002) the lower part of the La Vida Member with diabase sills and the Diamond Bar sandstone and siltstone to constitute the rift-fill sequence of a half-graben (the Puente Hills half-graben) that was active from ca. 14 to 10 Ma (Fig. 2, inset). Movements on the proto-

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Figure 1. Index map of Los Angeles basin showing northeastern Los Angeles basin, which is centered on the Puente Hills and the surrounding uplifts. Star is epicenter of Whittier Narrows earthquake (WN), Los Angeles (LA), San Gabriel Mountains (SGM), Santa Monica Mountains (SMM), American Petrofina Central C.H. No. 1 (CH1), Faults: Chino (Ch), Christianitos (C), El Modeno (EM), Newport-Inglewood (Ni), San Andreas (SA), San Gabriel (SG), Whittier (W). Well data and surface geology in all figures is after Shilton (1955), Yerkes (1957), Durham and Yerkes (1962), Yerkes (1972), Lang (1976), Schoellhamer et al. (1981), Yeats and Beall (1991), and West and Redin (1991).
Whittier normal fault, which bounded the Puente Hills half-graben to the southwest, generated the accommodation space in which the rift fill accumulated. That fault later moved in a reverse sense and became the currently active Whittier fault, inverting the Puente Hills half-graben.

**GLENORDA VOLCANICS**

The Glendora Volcanics, which attain a maximum known thickness of 1130 m in the Texaco Garnier 1 well (Fig. 4), both underlie and are interbedded with sedimentary rocks of the Topanga Formation (Fig. 2; Shelton, 1955). The rocks are mostly low-K andesite, but more than 20 compositions ranging from basalt to dacite have been identified (Shelton, 1955; Weigand, 1994). Lower units of the Glendora Volcanics have yielded an age of ca. 16 Ma (Nourse et al., 1998). Because the age of the Topanga Formation is 17.1–13.5 Ma, based on the presence of Lusitan and Relizian microfauna (Blake, 1991; Barron and Isacs, 2001), the Glendora Volcanics interbedded within the Topanga could be as young as ca. 14 Ma.

The known Glendora volcanic field trends northeast-southwest from outcrops near the San Gabriel Mountains foothills to the vicinity of the Whittier Narrows (Fig. 4). The Conoco Buehler I well (Fig. 4) penetrated 170 m of mafic igneous rocks with interbedded sandstones containing foraminifer of Relizian (17.1–15.7 Ma) and Lusitan (15.7–13.5 Ma) age (Davies and Woodford, 1949; Barron and Isacs, 2001). This incomplete penetration is our most southwest control point for the extent of the Glendora rocks.

**EL MODENO VOLCANICS**

El Modeno Volcanics crop out on the western flank of the Santa Ana Mountains and can be followed in the subsurface as far to the northwest as the Leffingwell oil field (Pyramid Oil K 1 well) (Yerkes, 1957) (Fig. 4). According to Yerkes (1957), El Modeno rocks are conformably overlain by the La Vida Member and conformably overlie the Topanga Formation (Fig. 2). The volcanic series includes medium- to basalt, tuff, and andesite (Yerkes, 1957; Weigand, 1994). Most well, including Shell Matthews 1 (Fig. 4), from which the maximum known thickness of 315 m is reported, have penetrated only the upper part of the El Modeno Volcanics. For that reason, although the extent of the volcanic rocks can be approximately mapped, their total thickness is not known.

An age of ca. 11 Ma from a volcanic rock in the upper part of El Modeno Volcanics was reported by Layendyk et al. (1998) using the \(^{40}Ar/^{39}Ar\) method. An early to middle Lusitan age (15.7–14.9 Ma) assigned to a rich foraminiferal fauna in a lower interbedded claystone (Yerkes, 1957; Barron and Isacs, 2001) is more compatible with an older K-Ar age determination of ca. 12.1–15.3 Ma (Weigand, 1982, recalculated from Turner, 1970) for an
upper volcanic unit. We have followed the faunal evidence and use an age of ca. 14 Ma for the El Modeno Volcanics. Ages of ca. 16–14 Ma for Glendora and El Modeno volcanic rocks led Weigand and Savage (1993) to argue that those rocks were too young to have been related to subduction involving the Farallon plate and were erupted under extensional conditions during transrotation of the western Transverse Ranges.

UPPER CRUSTAL P-WAVE VELOCITY ANOMALY

Zhou (1994) used travelt ime tomography to construct a high-resolution three-dimensional model for crustal P- and S-wave velocities in southern California. The dataset consists of more than 33,000 earthquakes with more than 1,000,000 P-wave arrivals and more than 130,000 S-wave arrivals. The model contains 18,720 blocks with dimensions of 10 × 10 × 3 km³. The master station ray-tracing method used is especially effective in dealing with large lateral velocity heterogeneities such as those beneath the northeastern Los Angeles basin. Due to the dense distributions of earthquakes and seismological stations in the region, most areas are well covered by ray paths; hence tomograms are robust to a depth of at least 20 km.

Higher than average velocity (6.63 km/s, 4%-8% above average) occurs in the model beneath the northwestern part of the Puente Hills half-graben (Figs. 3B and 4) (cf. Hauksson and Hase, 1997). It occupies a column of three vertically stacked model blocks at depths between 9 and 18 km. A separate high-velocity anomaly consisting of a southeast-trending layer of four blocks at a depth of 9–12 km is below the El Modeno volcanic field (Figs. 3A and 4).

We interpret the high-velocity tomographic anomalies of the northeastern Los Angeles basin to reflect the presence of a vertical, stocklike pluton and a tabular, sill-like pluton that are here named the Whittier Narrows and El Modeno plutons, respectively. We suggest that both plutons were emplaced into the upper crust during the Miocene and acted as magma sources for volcanic rocks. Rock with a bulk density of ~2.9 gm/cm³ and dioritic composition would correlate with the average block velocity (6.6 km/s) of both plutons (Birch, 1960).

Models of the evolution of the Los Angeles basin infer the existence of a rift boundary that accommodated the clockwise rotation of the western Transverse Ranges. Proposed locations of such a boundary range from the Newport-Inglewood fault zone in the southern Los Angeles basin to the San Gabriel–Chino–Christianitos faults north and east of the basin (Yeats et al., 1974; Crouch and Suppe, 1995; Nicholson et al., 1994; Wright, 1991; Ingersoll and Rummelhart, 1999) (Fig. 1). The 50-km-long northwest-trending crustal region into which the Whittier Narrows and El Modeno plutons were emplaced might mark the location of that rift boundary (Fig. 4). The geometry of such a boundary and its relationship to any related footwall detachment surface are not determined.

EVENTS IN THE NORTHEASTERN LOS ANGELES BASIN BETWEEN CA. 16 AND 7 Ma

16–14 Ma

The Glendora Volcanics, possibly erupted from the Whittier Narrows pluton, are now preserved in a 350 km² rectangular area with a northeastward trend (Fig. 4). This eruption was the first event indicative of extension in what had been a forearc environment (Dickinson, 1997, p. 942). Sediments of the Topanga Formation overlapped the first erupted Glendora volcanic rocks, and the processes of volcanic eruption and sediment deposition continued together for almost 2 m.y. (Fig. 5).

Ca. 14 Ma

As extension continued in the northeastern Los Angeles basin, igneous activity shifted to an area southeast of the Glendora volcanic field with the eruption of the El Modeno Volcanics from several discrete centers (Figs. 4 and 5). This second volcanic episode extended at least 200 km² along a northwest-southeast–trending belt, which is closely coincident with the underlying El Modeno pluton.
14–7 Ma

Structural, depositional, and igneous activity became concentrated within the 225 km² area of the west-northwest–trending Puente Hills half-graben (Fig. 2). That activity included formation of the Puente Hills half-graben across the proto-Whittier fault; deposition of strata of the La Vida Member; and intrusion of diabase sills into the La Vida rift fill. The Whittier Narrows pluton was in the right place to have contributed to the eruption of the diabase intrusives, possibly by feeding magma into La Vida strata along the plane of the proto-Whittier fault (Durham and Yerkes, 1964, p. B24). We suggest that diabase intrusion was over by 7 Ma, when a new tectonic phase began with deposition of Sycamore Canyon strata and the inversion of the Puente Hills half-graben (Fig. 5).

INFLUENCE OF EXTENSIONAL STRUCTURES ON THE ACTIVE TECTONICS OF THE NORTHEASTERN LOS ANGELES BASIN

Early-formed extension-related structures have played controlling roles in later tectonics of the northeastern Los Angeles basin. Most prominently, the proto-Whittier fault moved in a reverse sense to become the active Whittier fault, while related folding led to formation of the Puente Hills anticline (Fig. 5). A less appreciated controlled role may have been played by the Whittier Narrows pluton as a buttress in the segmentation of three active faults that terminate near the Whittier Narrows. They are the Puente Hills blind thrust, a segment of which may have caused the Whittier Narrows earthquake (1987, Mw = 5.9) (Hauksson and Jones, 1989; Shaw and Shearer, 1999); the El Paseo Park blind thrust (Osaki et al., 2000); and the Whittier fault (Wright, 1991). At a depth of 10 km, the approximate termination point (tip line) of each of these faults is located near the stocklike Whittier Narrows pluton (Fig. 4, A and B).

CONCLUSIONS

The now inverted Puente Hills half-graben and associated volcanic rocks characterize in time and space the initial extension in the Los Angeles basin. The extrusion of Miocene volcanic rocks in the northeastern Los Angeles basin and the intrusion of sills into sedimentary strata of the Puente Hills half-graben may closely define the duration of extension in the basin as occurring from ca. 16 to 7 Ma. Deep crust with anomalously high P-wave velocities, which we attribute to Miocene dioritic plutons, may have played a role in feeding the overlying volcanic rocks and sills. The 50-km-long northwest alignment of the interpreted dioritic plutons may mark the location of the northeastern Los Angeles basin rift boundary. The rift architecture of the proto-Whittier fault system and the shapes and locations of the interpreted plutons provide broad insights into the active tectonics of the Los Angeles basin. The northward dip of the modern Whittier fault may extend through the entire seis-mogenic crust and thereby have critical effect on estimates of earthquake hazard. The location of the stocklike Whittier Narrows pluton near the tip lines of three active faults suggests to us that plutons may be of general importance in the segmentation of active faults both in southern California and worldwide.

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