Crustal structure and tectonics from the Los Angeles basin to the Mojave Desert, southern California

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ABSTRACT

A seismic refraction and low-fold reflection survey, known as the Los Angeles Region Seismic Experiment (LARSE), was conducted along a transect (line 1) extending from Seal Beach, California, to the Mojave Desert, crossing the Los Angeles and San Gabriel Valley basins and San Gabriel Mountains. The chief result of this survey is an interpreted cross section that addresses a number of questions regarding the crustal structure and tectonics of southern California that have been debated for decades and have important implications for earthquake hazard assessment. The results (or constraints) are as follows. (1) The maximum depth of the Los Angeles basin along line 1 is 8–9 km. (2) The deep structure of the Sierra Madre fault zone in the northern San Gabriel Valley is as follows. The Duarte branch of the Sierra Madre fault zone forms a buried, 2.5-km-high, moderately north dipping buttress between the sedimentary and volcanic rocks of the San Gabriel Valley and the igneous and metamorphic rocks of the San Gabriel Mountains. (For deeper structure, see following.) (3) There are active crustal décollements in southern California. At middle-crustal depths, the Sierra Madre fault zone appears to sole into a master décollement that terminates northward at the San Andreas fault and projects southward beneath the San Gabriel Valley to the Puente Hills blind thrust fault. (4) The dip and depth extent of the San Andreas fault along line 1 dips steeply (~83°) northward and extends to at least the Moho. (5) The subsurface lateral extent of the Pelona Schist in southern California is as follows. Along line 1, the Pelona Schist underlies much, if not all of the San Gabriel Mountains south of the San Andreas fault to middle-crustal depths. North of the San Andreas fault, it is apparently not present along the transect.

Keywords: crustal structure, tectonics, continental margin, mountain building, southern California.

INTRODUCTION

Southern California is a region of great earthquake hazard, where answers to questions on deep crustal structure and tectonics would aid greatly in assessment of this hazard. Olsen et al. (1995) and Wald and Graves (1998) showed the importance of knowing sedimentary-basin depth in calculating surface shaking due to earthquakes. The Working Group on California Earthquake Probabilities (1995) discussed the importance of knowing fault structure both laterally and vertically in assessing hazards. Especially important is knowing the existence and location of blind thrust faults and related deeper, active décollements. Numerous authors have used seismologic and structural geologic data to infer the existence of active, deep-crustal décollements (e.g., Hadley and Kanamori, 1978; Yeats, 1981; Davis et al., 1989; and Shaw and Suppe, 1996), but obtaining a confirming image is more difficult. The presence of the Pelona Schist beneath a regional inactive décollement (the Vincent–Chocolate Mountains–Rand thrust fault) has been discussed by, e.g., Haxel and Dillon (1978), but Yeats (1981) and the Working Group on California Earthquake Probabilities (1995, their Fig. 4) also speculated that bodies of the Pelona and related Catalina Schist underlie a middle-crustal active décollement. Thus, the lateral and vertical distribution of these schists may be important in understanding deep décollements in southern California.

The Los Angeles Region Seismic Experiment (LARSE) was designed to address the questions raised here. In 1994, refraction and low-fold reflection data were recorded along a transect (line 1) extending from Seal Beach northeastward across the Los Angeles region to the Mojave Desert (Fig. 1). Fuis et al. (1996) gave an overview of these seismic images. Ryberg and Fuis (1998) produced a low-fold reflection image of the middle and lower crust, and Lutter et al. (1999) produced a tomographic image of the upper crust. In this paper we sharpen and extend the image of Lutter et al. (1999) to the mantle by modeling both refractions and reflections. In addition, we have reprocessed the reflection image of Ryberg and Fuis (1998) by using our new velocity model, and have combined these results into a synthesis model.

GEOLOGIC SETTING

From southwest to the northeast, LARSE line 1 crosses the Los Angeles basin, San Gabriel Valley basin, San Gabriel Mountains, and Mojave Desert (Fig. 1). The Los Angeles and San Gabriel Valley basins evolved in Neogene time during a pre-modern San Andreas phase of transform motion along the west margin of North America that involved opening of sedimentary basins (Wright, 1991). Oil-well drilling in the Los Angeles basin has penetrated as much as 6 km of sedimentary rocks (Wright, 1991), but the estimated maximum depth of these rocks is ~10 km (Yerkes et al., 1965). Wright (1991) estimated the maximum depth of sedimentary rocks in the San Gabriel Valley to be 3 km, and recently released oil-well data (Brocher et al., 1998) indicating a similar number (3.7 km). The Los Angeles and San Gabriel Valley basins are separated by the (active) Whittier fault and an uplifted block of igneous and metamorphic rocks (Yerkes, 1972).

The San Gabriel Mountains trend east (Fig. 1) in the central part of the Transverse Range province, which consists of two terranes, the Mesozoic Pelona Schist (lower plate) and a complex of Precambrian to Cenozoic igneous and metamorphic rocks (upper plate), separated by the (inactive) Vincent thrust fault (Ehlig, 1981). This range is bounded on the south by the (active) north-dipping Sierra Madre fault zone (Crook et al., 1987) and on the north by the steeply dipping San Andreas fault zone.

The San Gabriel Mountains block is juxtaposed on the north with the Mojave Desert block, composed of Mesozoic metamorphic and batholithic rocks and Cenozoic volcanic and sedimentary rocks (see Jennings, 1977). In scattered locations in the western and southeastern Mojave Desert, Pelona Schist is exposed in fensters in these igneous and metamorphic rocks, leading to speculation that the entire Mojave
Desert region may be underlain by Pelona Schist (Haxel and Dillon, 1978).

Tectonic models of southern California have proposed the existence of middle-crustal décollements beneath the Transverse Ranges that drive displacements on mapped and blind thrust faults in the sedimentary basins to the south (Hadley and Kanamori, 1978; Yeats, 1981; Davis et al., 1989; Davis and Namson, 1994). The 1987 M 5.9 Whittier Narrows earthquake (Hauksson et al., 1988) is interpreted to have occurred on such a blind thrust fault near line 1 (Davis et al., 1989; the Puente Hills blind-thrust fault of Shaw and Shearer, 1999). The bright reflective zone beneath the San Gabriel Mountains studied by Ryberg and Fuis (1998) may be evidence of such a middle-crustal décollement that is connected to the Puente Hills blind thrust fault.

**REFLECTION IMAGE**

The LARSE data (Murphy et al., 1996) were processed to produce a low-fold reflection image of the San Gabriel Mountains (Fig. 2, A–A'; see loose insert). In this image, envelopes of seismograms were stacked, rather than the seismograms themselves, as described by Ryberg and Fuis (1998). In the highest-fold region (10–40 fold), between the 45 and 85 km model coordinates, the chief reflective features (labeled A and B in Fig. 2A; see loose insert) are flat to gently convex upward, ~3 km thick by 10–20 km long, and arranged so that B represents a step upward from A of 3–4 km. A faint reflector projects from the top of B toward the Whittier Narrows hypocenter (Fig. 2A', white arrow; see loose insert). Feature C is a diffuse, south-dipping zone ~5 km thick in the vicinity of the Moho. When a line drawing of this envelope stack is constructed and migrated, the convex features A and B contract and represent less clearly a step, and feature C moves upward and northward (Ryberg and Fuis, 1998).

**FORWARD MODELING AND DISCUSSION**

A two-dimensional forward model (Fig. 2B; see loose insert) was constructed by using the inverse model of Lutter et al. (1999) as a starting upper crust model (<5 km depth) that was extended to the upper mantle by using middle-crustal and Moho reflections and mantle refractions. Constraints were added to the upper crustal part of the model, including outcrop data, oil-well data (Brocher et al., 1998), and industry reflection data (J.H. Shaw, 1998, personal commun.). The layered starting model was ray traced and adjusted to fit first arrivals and reflections to within ~0.05 s, although some mismatches of 0.10–0.15 s persist (more commonly for middle-crustal and deeper reflections). In this type of forward modeling, velocities are estimated to be accurate to 2%–3%, and boundary depths, are estimated to be accurate to 5%–10% (see discussion in Fuis et al., 1991). Documentation of the velocity model presented here was provided by N.J. Godfrey (2000, written commun.).

**Upper Crust**

In many places along line 1, the upper crust was adequately modeled (0.03 s average error) by the inversion of first-arrival data (Lutter et al., 1999), but forward modeling has added some important details.

1. Along line 1, the Los Angeles basin has a maximum depth of 8–9 km, consistent with estimates based chiefly on oil-well data (Yerkes et al., 1965). To the northwest, the basin may deepen. Basement (igneous and metamorphic rocks) beneath the Los Angeles basin is interpreted to be located at the level of a strong velocity gradient (an increase from 5.5 to 6.1 km/s) and wide-angle reflection at 8–9 km depth (Fig. 2B; see loose insert).

2. The San Gabriel Valley basin reaches a maximum depth of 5 km (Fig. 2, B and C; see loose insert), ~2 km deeper than the estimate of Wright (1991). One oil well penetrates granitoid basement (5.3–5.5 km/s) at 3.7 km depth in the southern San Gabriel Valley (Fig. 2C; see loose insert). Note that the steeply north dipping Whittier fault forms the south boundary of this basement block, beneath the Puente Hills; the dip of the fault (70°) is consistent with that seen in oil wells (Yerkes, 1972).

3. The Duarte branch of the Sierra Madre fault zone is associated with a buried scarp that offsets velocity contours by ~2.5 km (higher velocities on the north; Fig. 2, B and C; see loose insert). A moderately north dipping, tabular low-velocity zone extends to at least 5 km depth in basement rocks from the base of this scarp and is interpreted as the
to high-velocity basement rocks (6.1–6.8 km/s) beneath the San Gabriel Mountains (6.5–6.7 km/s) suggests maﬁc rocks, and lower crust beneath rocks of the Mojave Desert (6.3 km/s) suggests felsic to intermediate rocks, overlying a relatively low velocity unit (5.8–6.0 km/s), interpreted to be the Pelona Schist. These two plates are separated by a sharp reﬂector, interpreted to be the Vincent thrust fault (Fuis et al., 2001).

5. Upper crustal structure in the Mojave Desert is not as well determined as structure in the San Gabriel Mountains, owing to a lower density of shotpoints (Fig. 1). Depths of sedimentary basins were modeled by carefully matching ﬁrst arrivals near shotpoints, where available, and by estimates based on local geology, where no shotpoints were available. Velocities to 10 km depth are consistently higher than average laboratory velocities for the Pelona Schist (see McCaffree Pellicer and Christensen, 1998; Lutter et al., 1999). Thus, in spite of the scattered occurrences of Pelona Schist and its equivalents structurally below rocks of the Mojave Desert (Haxel and Dillon, 1978), signiﬁcant bodies of the Pelona Schist do not appear to be present in the Mojave Desert beneath line 1. This conclusion is also supported by aeromagnetic data along the transect, which indicate that the upper ~8 km of the Mojave Desert is magnetic and cannot include the weakly magnetic Pelona Schist (Langenheim, 1999).

**Middle Crust**

Several individual reﬂectors are modeled in the middle crust (Fig. 2B; see loose insert). South of the San Andreas fault, three reﬂectors are seen near the top of the bright reﬂective zone (see Fig. 2A; see loose insert). North of the San Andreas fault, three reﬂectors are also modeled at the same approximate level in the crust, but are unconnected with reﬂectors to the south. (Reﬂection bottoming points are not continuous between reﬂectors north and south of the San Andreas fault.) Thus, we conclude that the San Andreas fault is a discontinuity to at least middle-crustal depths. The deepest of the reﬂectors of the San Andreas fault terminates ~3 km north of the surface trace of the San Andreas fault, leading to our interpretation that the San Andreas fault dips ~83° N on average through the upper and middle crust. In addition, two-way traveltimes to the reﬂectors from two shotpoints north of the San Andreas support a narrow tabular zone of relatively low velocity (5.8 km/s) from below the trace of the San Andreas fault to middle-crustal depths.

A study of reﬂector amplitudes indicates that P-wave velocity falls by as much as 1.7 km/s in a zone ~500 m thick at the top of bright zone A (Ryberg and Fuis, 1998). Other such thin, low-velocity zones may be present at greater depth in zone A. Such a velocity drop almost requires the presence of ﬂuids, probably in macroscopic cracks at near-lithostatic pressure. Other possibilities include magma and serpentinite, but the nearest active volcanism is more than 100 km distant, and serpentinite is a minor rock type in the San Gabriel Mountains. The weakness in the crust implied by such a ﬂuid-ﬁlled zone might be associated with faulting (e.g., Sibson, 1992, 1994; Hickman et al., 1995), and Ryberg and Fuis (1998) hypothesized that a shallowly dipping fault, or décollement, connects these with the hypocentral region of the Whittier Narrows earthquake. This hypothesis is supported by the gentle north dip of the uppermost middle-crustal reﬂector (Fig. 2B), and by a faint north-dipping reﬂector at the top of bright zone B (Fig. 2A’, white arrow; see loose insert). The Sierra Madre fault zone would sole into this master décollement. At a depth of 19–20 km, this décollement is near the base of the brittle zone of the crust, on the basis of seismicity (Fig. 2, A and B; see loose insert), and may represent a decoupling zone between upper and lower crust (Fig. 3). In such a tectonic model, the upper crust behaves as brittle blocks that are displaced by thrust and strike-slip faults, and the lower crust ﬂows toward the San Andreas fault to create a root centered at the fault. In an alternative interpretation of fault geometry, the Sierra Madre fault zone offsets, in the wrong sense, the two bright zones A and B.

As a graphic illustration of our preferred tectonic model, we modeled a simpliﬁed version of the upper crust as an assemblage of foam-rubber blocks resting on a décollement (Fig. 4; see loose insert, originally done for a public display). As these blocks are compressed in the approximate direction of convergence between the Paciﬁc and North American plates, one sees right-lateral displacement on the San Andreas fault and oblique motion on the Sierra Madre and Whittier faults. It is signiﬁcant that one sees two voids, a large one beneath the San Gabriel Mountains block and a small one beneath the Puente Hills–San Gabriel Valley block, created as those blocks move upward on their frontal faults. These voids would represent the two bright zones, A and B, in the real Earth, each with ﬂuid-ﬁlled cracks.

**Lower Crust and Mantle**

Lower crustal velocities and Moho geometry are determined from wide-angle reﬂections (PnMP) and to a lesser extent by mantle reﬂections (Pn). The lower crust of the Los Angeles basin and San Gabriel Mountains (6.5–6.7 km/s) suggests mafic rocks, and lower crust beneath the Mojave Desert (6.3 km/s) suggests felsic to intermediate rocks (see Christensen and Mooney, 1995). There is a poorly resolved contrast in lower crustal velocities across the deep projection of the San Andreas fault (6.57 km/s on the south; 6.3 km/s on the north),

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**Figure 3.** Schematic block diagram showing interpreted tectonics in vicinity of LARSE line 1. Active faults are shown in orange, and moderate and large earthquakes are shown with orange stars and attached dates, magnitudes, and names. Gray half-arrows show relative motions on faults. Small white arrows show block motions in vicinities of bright reﬂective zones A and B (see Fig. 2A). Large white arrows show relative convergence direction of Paciﬁc and North American plates. We interpret a master décollement ascending from bright reﬂective zone A at San Andreas fault, above which brittle upper crust is imbricating along thrust and reverse faults and below which lower crust is ﬂowing toward San Andreas fault (brown arrows) and depressing Moho. Fluid injection, indicated by small lentil-like blue areas, is envisioned in bright reﬂective zones A and B.
suggesting that the San Andreas fault extends to the Moho. The nature and geometry of the San Andreas fault in the lower crust are unknown.

SUMMARY

The LARSE transect from the Los Angeles basin to the Mojave Desert addresses several important questions concerning the crustal structure and tectonics of southern California. Answers to these questions have implications for earthquake hazard assessment. The depths and configurations of sedimentary basins affect earthquake shaking observed at the surface. LARSE has imaged the Los Angeles and San Gabriel Valley basins and has found maximum depths along the transect of 8–9 and 5 km, respectively. Both basins have steeply north dipping buttress-like boundaries on their northern margins that are identified with the Whittier and Sierra Madre (Duarte) faults. The Pelona Schist, which underlies an inactive décollement in the San Gabriel Mountains and in scattered areas of the Mojave Desert, underlies most if not all of the San Gabriel Mountains (south of the San Andreas fault) to mid-crustal depths, but is not present at depth along the LARSE transect in the Mojave Desert. The deep fault structure of the San Gabriel Mountains appears to be as follows. The Sierra Madre fault zone and Puente Hills blind thrust fault sole into a middle-crustal décollement that originates at the San Andreas fault. A companion décollement is seen in the southern Mojave Desert. In this tectonic model, ductile lower crust flows toward the San Andreas fault beneath these décollements, from both north and south directions, creating a crustal root centered beneath the trace of the San Andreas fault.

ACKNOWLEDGMENTS

We reiterate our thanks to the field crew that collected the LARSE data set, acknowledged in Murphy et al. (1996), especially Ed Cirely, manager of the field operations. We thank reviewers Thomas Brocher, Randy Keller, Walter Mooney, and John Shaw. We thank the Deutsche Forschungsgemeinschaft (DFG) for funding for one of us (Ryberg) and the Southern California Earthquake Center (SCEC), U.S. Geological Survey (USGS), and National Science Foundation (NSF) for funding for two of us (Godfrey and Okaya; NSF Cooperative Agreement EAR-8920136 and USGS Cooperative Agreements 14-08-0001-A0899 and 1434-HQ-97AG0178). This is SCEC contribution 538.

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Manuscript received June 15, 2000

Manuscript received September 28, 2000

Manuscript accepted October 3, 2000

Printed in USA