Structural transect of the western Transverse Ranges, California: Implications for lithospheric kinematics and seismic risk evaluation

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ABSTRACT

A retrodeformable cross section that integrates surface and subsurface data across the western Transverse Ranges, California, illustrates an actively developing fold and thrust belt that began forming at 2–3 Ma. High-level thrusts are interpreted to root in a mid-crustal detachment at 12–15 km depth, which coincides with the maximum depth of earthquakes. The cross section documents 53 km of convergence above the mid-crustal detachment; dividing this by the time since onset of deformation yields convergence rates of 17.6–26.5 mm/yr. The high-density lithospheric anomaly beneath the Transverse Ranges is related to subduction of lower crust and lithosphere below the mid-crustal detachment to balance the shallow crustal shortening. Thrust ramps coincide with zones of high seismicity in the Transverse Ranges; this suggests that ramp regions have the highest potential for compressive earthquake events: e.g., the recent Whittier Narrows earthquake of October 1, 1987 (M_l = 5.9), occurred along the eastern part of a ramp zone.

INTRODUCTION

The Transverse Ranges of southern California consist of a series of young, east-west–trending ranges and valleys that cut across the northwest-trending topography of California. The ranges are underlain by a thick sequence of late Mesozoic and Cenozoic age strata that rest unconformably on a variety of basement types. The Transverse Ranges are undergoing active north-south shortening as documented by late Pliocene and Quaternary folds, thrust faults, and reverse faults (Reed and Hollister, 1936; Jahns, 1954; Dibblee, 1982a), geodetically measured north-south convergence (Savage et al., 1986; Christodoulidis et al., 1985), and numerous compressive earthquake events with north-south–directed P-axes (Hadley and Kanamori, 1977; Yerkes and Lee, 1979; Webb and Kanamori, 1985).

Geophysical studies of the Transverse Ranges reveal several features of the lithospheric structure: (1) The majority of earthquakes occur above 12–15 km (Hadley and Kanamori, 1977). (2) Seismic studies indicate an east-west–trending, slab-shaped, high-velocity anomaly within the upper mantle (Hadley and Kanamori, 1977; Raikes, 1980; Humphreys et al., 1984). (3) Gravity studies indicate an east-west–trending, high-density gravity anomaly under the central Transverse Ranges (Sheffels and McNutt, 1986).

Several geophysical and geological models have been proposed to explain the above observations. The 12–15 km seismicity floor and the low-angle, compressive earthquake mechanisms have been interpreted to coincide with a mid-crustal, subhorizontal detachment (Hadley and Kanamori, 1977; Webb and Kanamori, 1985). On the basis of regional geologic relations and some of the previously mentioned geophysical observations, Yeats (1981, 1983) suggested that the reverse faults of the Transverse Ranges rooted into a mid-crustal detachment. Yeats (1981) further proposed that this detachment separated an upper brittle tectonic "flake" from a lower plate undergoing plastic deformation. Bird and Rosenstock (1984) developed a kinematic model of the Transverse Ranges using late Cenozoic slip rates that showed significant convergence in the western Transverse Ranges and predicted mantle-lithosphere downwelling, which is consistent with the observed upper-mantle seismic velocity and gravity anomalies.

In this paper we present a geologic model of the upper crust beneath the western Transverse Ranges (Fig. 1) based on a balanced regional cross section (Fig. 2a) that interprets the area to be an actively developing fold and thrust belt that began to form during late Pliocene time (2–3 Ma). We interpret the major map-scale folds to be fault-bend or fault-propagation folds (Suppe, 1985) developed above thrust faults stepping upsection from a regional detachment that coincides with the floor of seismicity. The regional cross section has been restored to late Pliocene time using the line-length method (Fig. 2b; Woodward et al., 1985). The retrodeformability of the cross section tests the internal consistency of the structural interpretation and shows that the section is balanced. The cross section and restoration are used to (1) estimate the amount of crustal convergence, (2) provide an independent estimate of the depth of the lithospheric anomaly, and (3) estimate the convergence rate across the western Transverse Ranges since late Pliocene time. Because the Transverse Ranges are seismically active, the cross section can be used to understand the relation between geologic structures and zones of seismicity.

The cross section is a two-dimensional solution that assumes minimal motion out of the plane of the cross section, with the exception of the San Andreas fault, during the past 3 m.y. We believe this assumption is compatible with the western Transverse Ranges geology, as we demonstrate in the following discussion.

CROSS-SECTION DESCRIPTION

The regional cross section was originally constructed at a scale of 1:24000 by using surface maps (Dibblee, 1982b, 1982c; California Division of Mines, 1973; Dibblee and Nilsen, 1973; Davis, 1983; Davis and Duebendorfer, 1987) integrated with well data from numerous oil fields and wildcat wells along the transect. These data constrain the fold and fault geometries that are used to construct the balanced interpretation. The Cenozoic structural history of the western Transverse Ranges is complex; here we focus only on the latest phase of north-south convergent deformation that developed during the past 2–3 m.y.

Starting at the south, the section begins in the West Montalvo oil field, which is part of an east-west anticlinal trend more than 60 km long. Anticlines along the trend are generally asymmetric, having steep north limbs and gentle south limbs. On the basis of the asymmetric shape of the anticline, the fold is interpreted to be a fault-propagation fold above the postulated South Mountain thrust. The Oak Ridge fault lies along the southern boundary of the Ventura basin and separates thick upper Miocene to Pleistocene strata of the basin on the north from a coeval but much thinner section to the south of the fault. At shallow levels the fault is south dipping, and it generally occurs on the north limb of the asymmetric anticlines. The Oak Ridge fault is interpreted to be a late Miocene to

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Pliocene north-dipping, normal fault (Namson, 1987) accommodating subsidence and sediment accumulation (Yeats, 1977). The present south dip of the upper part of the fault is the result of rotation by Quaternary anticlinal folding (Fig. 2a) and along strike to the west, the rotated part of the normal fault has been reactivated as a reverse fault (Namson, 1987).

The next major structure to the north is the Ventura Avenue anticline. The anticline has been interpreted to be rootless (Nagle and Parker, 1971), and Yeats (1983) interpreted the fold as detached above a ductile sequence of Miocene rocks. Namson (1987) interpreted the fold as a series of wedge-shaped imbricate thrusts that are rooted at the base of the Miocene (Fig. 2a), and slip on the basal Miocene detachment is derived from the thrust responsible for the adjacent Lion Mountain anticline. The Lion Mountain anticline is interpreted to be a fault-bend fold associated with a ramp on a buried splay of the San Cayetano fault (SCT1) which steps up from a lower detachment within the Cretaceous strata to an upper detachment at the base of the Miocene sequence. (The San Cayetano thrust comes to the surface about 10 km east of the cross section; see Fig. 1.) At the surface, the south limb of the Lion Mountain anticline is composed of a thick sequence of Oligocene through Pliocene strata, and the bedding-plane Lion Mountain fault occurs at the base of the Miocene sequence (Dibblee, 1982b). Slip on the upper detachment of the fault-bend fold (base of Miocene) is partitioned between the wedge-shaped imbricates responsible for the Ventura Avenue anticline and the Lion Mountain fault, which is a back thrust off the upper detachment.

North of the Lion Mountain anticline the Santa Ynez–Topatopa mountains are an east-west–trending anticlinal uplift more than 150 km long. Where the cross section intersects the range, the south limb of the antiform is overturned. Uplift and folding of the range occurred during the late Pliocene and Quaternary (Dibblee, 1982b; Yeats, 1983). The Santa Ynez fault occurs along the north flank of the Santa Ynez–Topatopa mountains and separates them from the San Rafael Mountains to the north. The Santa Ynez fault has been interpreted in various ways. McCulloh (1981) hypothesized left-slip movement of 37 km, which occurred mostly during Miocene time. In contrast, Hall (1981) believed the fault had considerable right slip during Miocene time. Gordon (1978) and Dibblee (1982b) suggested that the Santa Ynez is primarily a dip-slip fault and discounted the large amounts of strike slip because the fault terminates at both the eastern and western ends of the Santa Ynez–Topatopa mountains. We interpret the Santa Ynez fault as a north-vergent back thrust associated with a south-vergent Oligocene thrust system that uplifted the ancestral San Rafael Mountains (Reed and Hollister, 1936). This explains the origin of the regional angular unconformity between upper Oligocene through Miocene strata and upper Mesozoic through lower Tertiary strata, and gives a structural explanation for the Ynezian orogeny (Dibblee, 1982b; see Namson, 1987, for more detail). The configuration of the Oligocene thrust system is shown in the restoration (Fig. 2b).

The Quaternary antiformal structure of the Santa Ynez–Topatopa mountains is interpreted to be related to two stacked anticlines having cores of Cretaceous strata. The deeper anticline is a fault-bend fold associated with the lower splay of the San Cayetano thrust (SCT1), and the upper anticline is a fault-propagation fold associated with an upper splay of the San Cayetano thrust (SCT2, Fig. 2a). The splays merge downward into a common detachment of the main San Cayetano thrust. The Santa Ynez fault is folded and cut by Quaternary structures. Minor Quaternary reactivation of the Santa Ynez fault is interpreted as shearing associated with folding.

Between the Santa Ynez fault and the Pine Mountain thrust are several tight, small folds that terminate against the Pine Mountain thrust. Near its surface trace, the Pine Mountain thrust overrides the north limb of a syncline that contains strata as young as Pliocene. The syncline is interpreted to be the front of a fault-propagation fold on a splay of the Pine Mountain thrust. The Pine Mountain thrust is shown to root downward into the same detachment as the San Cayetano thrust system. The hanging wall of the Pine Mountain thrust is composed of a thick sequence of Eocene and Miocene strata that rest unconformably on granitic and gneissic basement of Alamo and Frazier mountains. The Miocene strata rest with angular discordance on moderately folded Eocene strata (Dibblee, 1982c). This regional unconformity is only moderately folded and does not dip as steeply as the underlying Eocene strata; it is probably associated with the Ynezian orogeny.

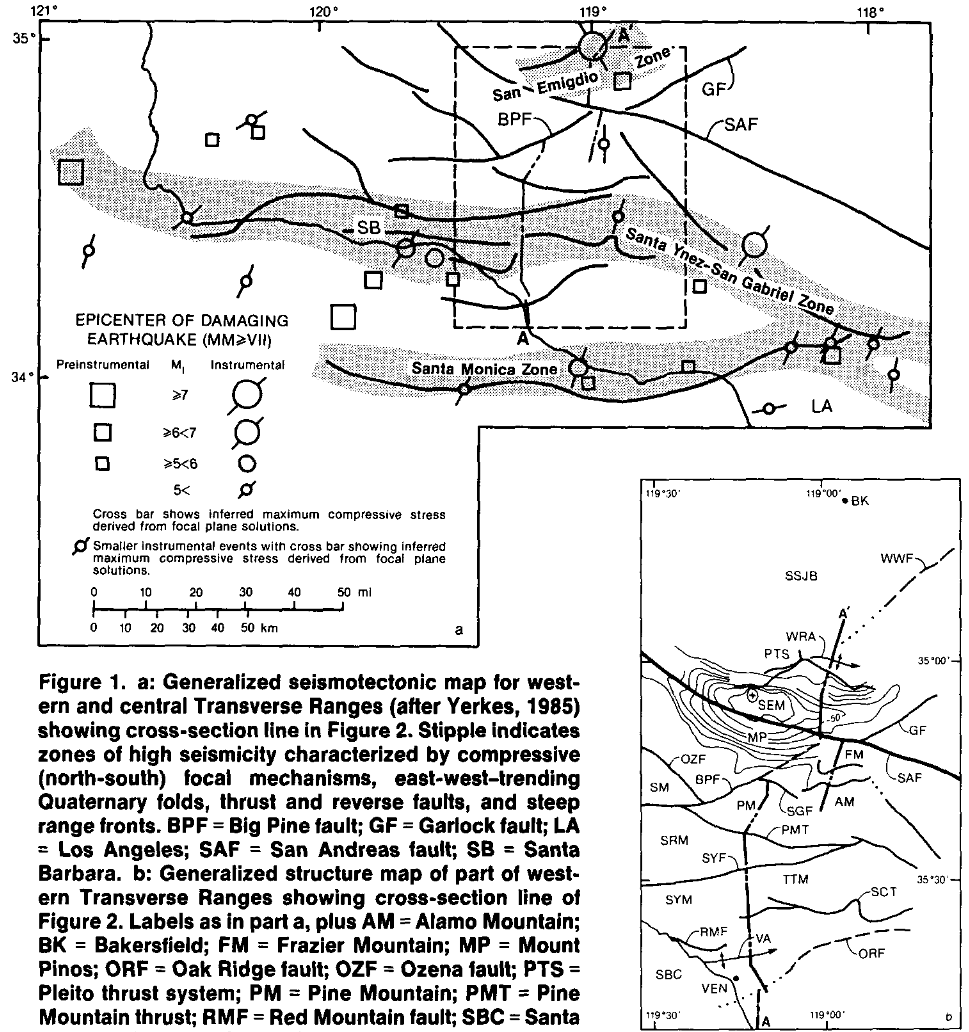


Figure 1. a: Generalized seismotectonic map for western and central Transverse Ranges (after Yerkes, 1985) showing cross-section line in Figure 2. Stipple indicates zones of high seismicity characterized by compressive (north-south) focal mechanisms, east-west–trending Quaternary folds, thrust and reverse faults, and steep range fronts. BPF = Big Pine fault; GF = Garlock fault; LA = Los Angeles; SAF = San Andreas fault; SB = Santa Barbara. b: Generalized structure map of part of western Transverse Ranges showing cross-section line of Figure 2. Labels as in part a, plus AM = Alamo Mountain; BK = Bakersfield; FM = Frazier Mountain; MP = Mount Pinos; ORF = Oak Ridge fault; OZF = Ozena fault; PTS = Pleito thrust system; PM = Pine Mountain; PMT = Pine Mountain thrust; RMF = Red Mountain fault; SBC = Santa Barbara Channel; SCT = San Cayetano thrust; SEM = San Emigdio Mountains; SGF = San Guillermo thrust; SM = Sierra Madre; SRM = San Rafael Mountains; SSJB = southern San Joaquin basin; SYF = Santa Ynez fault; SYM = Santa Ynez Mountains; TTM = Topatopa Mountains; VA = Ventura Avenue anticline; VEN = Ventura; WRA = Wheeler Ridge anticline; WWF = White Wolf fault. Contour lines about SEM, MP, and SAF are lines of equal Bouguer anomaly (5 mgal).

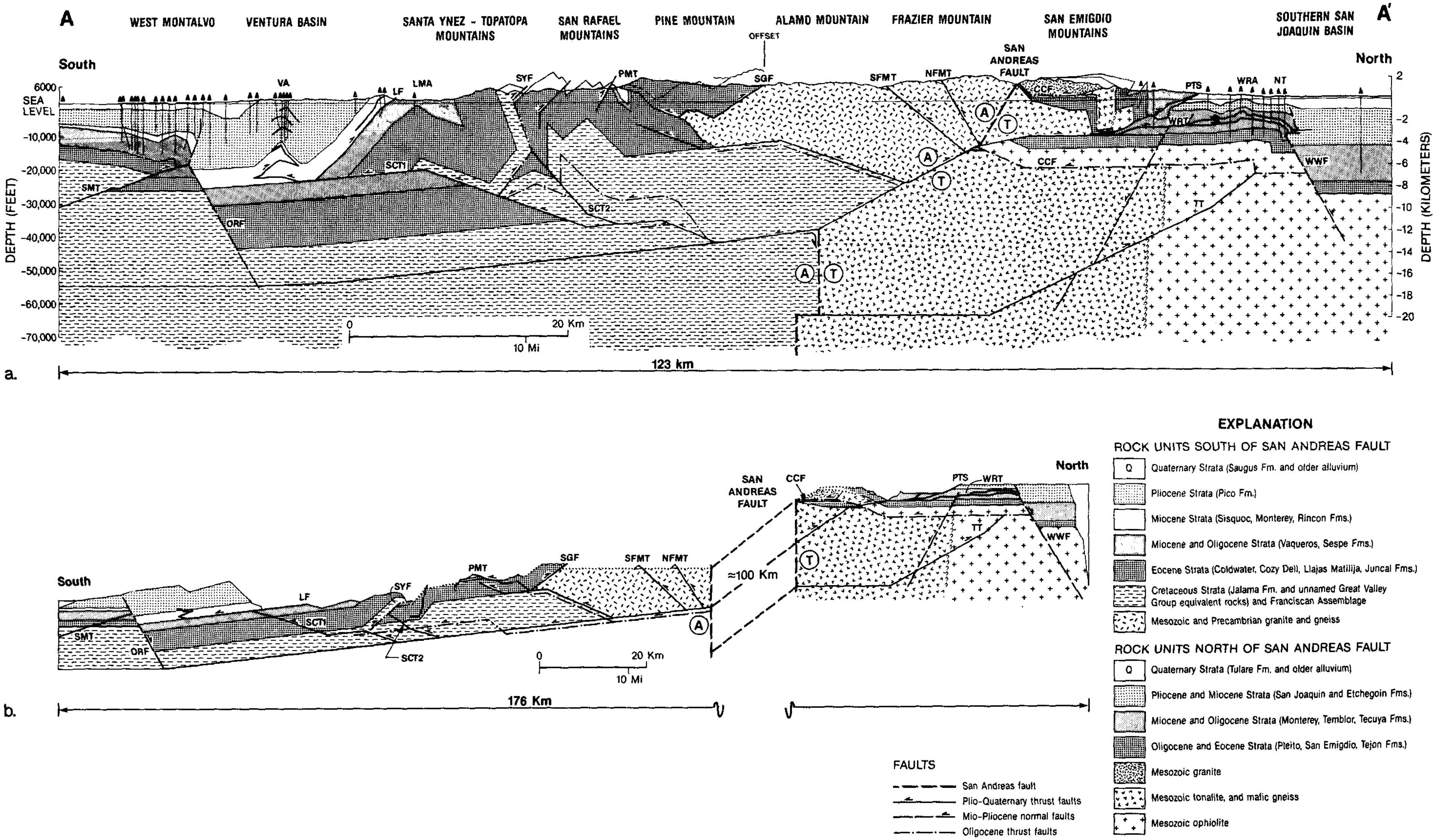


Figure 2. a: Structural transect across western Transverse Ranges. CCF = Caballo Canyon fault; LF = Lion fault; LMA = Lion Mountain anticline; NFMT = North Frazier Mountain thrust; NT = North Tejon oil field; ORF = Oak Ridge fault; PMT = Pine Mountain thrust; PTS = Pleito thrust system; SCT = San Cayetano thrust (SCT1 and SCT2 are splays); SFMT = South Frazier Mountain thrust; SGF = San Guillermo fault; SMT = South Mountain thrust; SYF = Santa Ynez fault; TT = Tejon thrust; VA = Ventura Avenue anticline; WRA = Wheeler Ridge anticline; WRT = Wheeler Ridge thrust; WWF = White Wolf fault. Circled A and T indicate motion of San Andreas fault. b: Line-length restoration of late Pliocene through Quaternary compressive structures of transect in part a. Comparison of transect length between deformed section (123 km) and restored section (176 km) yields 53 km of convergence since late Pliocene time (~3.0 Ma). This gives shortening of 30% and convergence rate of 17.6 mm/yr. Section indicates restored positions of Oligocene compressive structures, late Miocene–Pliocene normal faults, and San Andreas strike-slip offset. San Andreas fault restores to vertical fault, separating terrain now offset horizontally about 100 km. Labels as in a.

The cross section intersects the San Andreas fault between the Big Pine and Garlock faults; surface maps by Davis and Duebendorfer (1987) indicate that this part of the San Andreas fault is a narrow zone with no evidence of significant dip-slip offset. Well-constrained horizontally offset drainage lines in the nearby Carrizo Plain indicate right-lateral slip rates of 33.9 ±2.9 mm/yr for the past 3.7 ka and 35.8 +5.4/–4.1 mm/yr for the past 13.25 ka (Sieh and Jahns, 1984).

Adjacent to and directly north of the San Andreas fault is the north-dipping Caballo Canyon fault, which contains crystalline basement in the hanging wall and Oligocene strata in the footwall. Davis (1986) interpreted the Caballo Canyon fault to be a south-vergent thrust that lifted the ancestral San Emigdio Mountains during Oligocene time (Ynezian orogeny?). Along the north flank of the San Emigdio Mountains is the late Pliocene to Quaternary Pleito fault system, which consists of several south-dipping (20°–30°) thrust faults constrained by well data as deep as 3 km (Davis, 1983, 1986). Well data in this area show that major anticlines are formed by fault-bend or fault-propagation folding, and slip on some of the large thrusts does not reach the surface (Namson and Davis, 1988). For example, the Wheeler Ridge thrust ramps up across the Miocene sequence to form the Wheeler Ridge anticline, but the thrust never breaks the surface (Davis, 1986; Medwedeff, 1987). The splays of the Pleito fault system are shown to root at depth into one common detachment. Isopach mapping in the upper and lower plates of the main Pleito fault shows no evidence for strike-slip motion since Eocene time (Lagoe, 1987).

North of the Pleito fault system, the White Wolf fault separates upper Miocene and Pliocene strata of the San Emigdio Mountains from coeval but much thicker strata of the southern San Joaquin basin. Well data from the downthrown side of the White Wolf fault show the presence of shallow-marine and lacustrine rocks at 3–4 km depth. Other well data show the White Wolf fault to be a south-dipping reverse fault within the steeply dipping north flank of an asymmetric anticline of the North Tejon oil field. We interpret the White Wolf fault to be a late Miocene to Pliocene normal fault whose upper part has been subsequently folded. The asymmetric North Tejon anticline suggests that it is a fault-propagation fold above a north-vergent basement thrust. This thrust has the appropriate location, orientation, and sense of slip to be the cause of the 1952 Arvin-Tehachapi earthquake (M_l = 7.6; Davis and Lagoe, 1987). Movement on this thrust would also fit the area of coseismic topographic uplift (Stein and Thatcher, 1981).

The cross section shows the splays of the Pleito thrust system to root in a common detachment below the surface trace of the San Andreas fault. The shallow part of the San Andreas fault is interpreted to dip south and be detached (at 6.5 km) in the upper plate of the Pleito thrust system. Shallow and deep crustal parts of the San Andreas fault are offset along two mid-crustal ramps of the Pleito thrust system. The south dip and shallow detachment of the San Andreas fault are consistent with two observations. (1) Regional gravity study of the western big bend area reveals a large positive gravity anomaly with a crest located north of the San Andreas fault (SEM, Fig. 1b; Griscom and Oliver, 1980). The position of the crest corresponds to outcrops of dense basement rocks of ophiolite, tonalite, and mafic gneiss. The south flank of the anomaly does not terminate at the surface trace of the San Andreas fault but extends 5–6 km south of the San Andreas fault; this suggests that high-density rocks extend southward beneath the surface trace of the San Andreas fault for some distance. (2) The location of the topographically highest part of the western Transverse Ranges, the Mount Pinos and Frazier Mountain area, is located immediately above the large crustal ramp along which the San Andreas is shown to be detached.

IMPLICATIONS

The present-day length of the cross section is 123 km, and the restored length is 176 km. The cumulative convergence (restored length minus deformed length) totals 53 km (30% shortening); 34 km south and 19 km north of the San Andreas fault. The cumulative convergence is a minimum because the section does not extend offshore to the southern boundary of the Transverse Ranges.

The convergence values can be used to calculate average crustal convergence rates if the time convergence started is known. The onset of convergence can be no younger than 2.0 Ma (Ventura basin; Yeats, 1983), and regional stratigraphic evidence suggests that it is no older than 3.0 Ma (Crowell, 1966; Rockwell, 1982; Davis, 1983). By using this range of time values, the convergence rates north and south of the San Andreas fault are determined to be 6.3–9.5 mm/yr and 11.3–17.0 mm/yr, respectively. The total convergence rate across the onshore part of the western Transverse Ranges is 17.6–26.5 mm/yr.

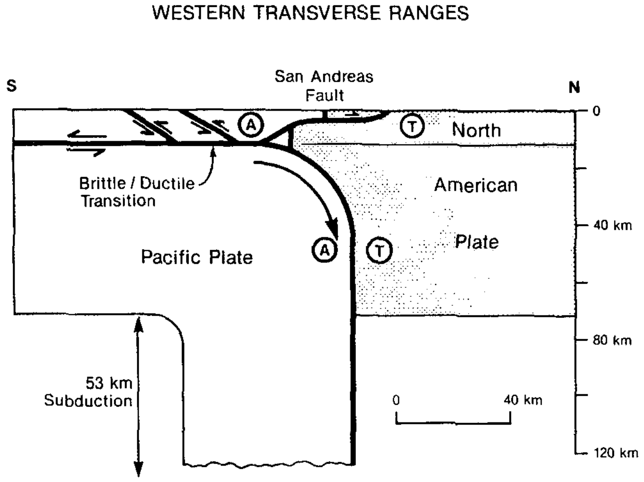
The convergence rate is useful for estimates of recurrence times of moderate to large earthquakes along north-south segments of the Transverse Ranges. If we assume no aseismic creep and that a thrust moves 1–2 m at depth during a moderate-size earthquake, then it would require an event every 57–113 yr along a north-south section to accommodate the estimated convergence rate (17.6 mm/yr) for 3.0 Ma. This recurrence interval is about an order of magnitude greater than that derived by Yeats and Berryman (1987). The general application of using balanced cross sections to estimate recurrence times can be applied to specific structures (Namson and Davis, 1986) and should be combined with other methods to better forecast both the time and location of future earthquakes.

An important implication of crustal shortening above the mid-crustal detachment is that the lower crust and lithosphere must be shortened or subducted an amount similar to the upper crust. We favor the model of Bird and Rosenstock (1984), in which the lower crust and mantle lithosphere are subducted to account for the shallow-level crustal shortening. The shortening values in this study suggest that a 53-km-long slab of lower crust and lithosphere should have been subducted beneath the western Transverse Ranges during the past 2–3 m.y. (Fig. 3). The size of the postulated subducted slab compares favorably with the 60-km-thick high-velocity region that dips steeply to a depth of 100–150 km beneath the western Transverse Ranges, observed from seismic tomography (Humphreys et al., 1984).

The cross section presents a useful structural framework for explaining the distribution, focal depths, and compressive focal mechanisms of earthquakes in the western and central Transverse Ranges. Yerkes (1985) showed the distribution of 42 known damaging earthquakes from 1800 to 1978 (MM >VII) in the Transverse Ranges; some of these are shown in Figure 1a. The distribution of these events defines three east-west-trending zones that coincide with structural trends: Santa Monica, Santa Ynez–San Gabriel, and San Emigdio. Known focal mechanisms for events within these zones are overwhelmingly compressive (Yerkes, 1985; Fig. 1a). The Whittier Narrows earthquake (M_l = 5.9) of October 1, 1987, occurred along the Santa Monica zone. The cross section traverses the latter two trends and indicates that the seismicity is concentrated along the major thrust ramps of the western Transverse Range transect. Many of these thrust ramps never reach the surface or reach the surface through complicated trajectories. It is therefore difficult, if not impossible, to evaluate their seismic potential from surface studies alone. Balanced cross sections that integrate surface and subsurface data are one technique that can determine the geometry and slip rates of thrusts for seismic risk evaluations.

A final implication of the cross section is that strike-slip motion along the San Andreas fault and north-south compressive motion on thrusts are contemporaneous. At the plate tectonic scale, this model suggests that the transpressive strain between the North American and Pacific plates in the western Transverse Ranges is resolved into two components. The strike-slip component is parallel to the plate boundary

Figure 3. Schematic cross section showing how shortening below mid-crustal detachment of Transverse Ranges is accommodated by subduction of lower crust and lithosphere of Pacific plate. Regional transect suggests that 53 km of subduction is necessary to balance shortening above detachment. Slab is 60 km thick, as suggested from seismic tomography (Humphreys et al., 1984), and extends to depth of about 120 km, which is consistent with observed high-velocity anomaly in western Transverse Ranges (Humphreys et al., 1984). A and T indicate motion of San Andreas fault.



(San Andreas fault and/or other strike-slip faults offshore). The compressional component is at a high angle to the San Andreas fault, parallel to the dip of thrust faults, and perpendicular to the axes of major late Pliocene to Quaternary folds. The resolution of displacements into orthogonal components is also recognized in the central California Coast Ranges (Namson and Davis, 1988) and is consistent with the present-day compressive stress field, which is perpendicular to the San Andreas fault (Mount and Suppe, 1987; Zoback et al., 1987).

CONCLUSIONS

1. The western Transverse Ranges are a seismically active fold and thrust belt, detached at 12–15 km, which has developed over the past 2–3 m.y. The shallow-level crustal shortening is balanced by subduction of the lower crust and lithosphere, as proposed by Bird and Rosenstock (1984).

2. A retrodeformable cross section yields a convergence of 53 km across the belt. This amount of shortening is in good agreement with the depth of the high-density slab as imaged from seismic tomography (Humphreys et al., 1984).

3. If we assume that convergence began at 2–3 Ma, then convergence rates are 6.3–9.5 mm/yr north of the San Andreas fault, 11.3–17.0 mm/yr south of the fault, and 17.6–26.5 mm/yr across the onshore part of the western Transverse Ranges.

4. Zones of compressive earthquakes within the western and central Transverse Ranges occur above major thrust ramps. Convergence rates along north-south segments suggest recurrence times of 50–100 yr for moderate earthquakes. Balanced cross sections are a powerful technique for determining the seismic risk associated with thrusts in active mountain belts.

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