Thom Davis

Seismically active fold and thrust belt in the San Joaquin Valley, central California

J. S. NAMSON
T. L. DAVIS* } *ARCO Oil and Gas Company, 2300 Plano Parkway, Plano, Texas 75075*

ABSTRACT

Structural analysis of late Cenozoic folds along the western and southern margins of the San Joaquin basin suggests that the folds are related to development of a fold and thrust belt rather than to wrench tectonics. The folds have formed by the processes of fault-bend folding and fault-propagation folding, which commonly occur in fold and thrust belts. Our structural interpretation attributes the seismically active Coalinga and Kettleman Hills North Dome anticlines to fault-bend folding above a thrust fault(s) that steps up from a detachment within the Franciscan Assemblage to a detachment at the base of the Great Valley Group. This thrust does not reach the surface (blind thrust), and its slip is consumed in backthrusting and formation of subsurface folds under the San Joaquin Valley. Movement on the postulated thrust(s) would explain the cause of the May 2, 1983, Coalinga earthquake and the August 15, 1985, Avenal earthquake and would account for the lack of significant surface rupture or shallow subsurface faulting during both earthquakes. Well-documented examples of fault-bend and fault-propagation folding also occur at Wheeler Ridge, in the San Emigdio Mountains, and at Kettleman Hills South Dome.

Deformation associated with fold and thrust belts can be extremely complicated. Considerable fault movement can occur without accompanying surface rupture or shallow-level faulting. Conversely, surface rupture can occur that has no direct relationship to fault slip at depth. An example would be flexural-slip folding wherein the slip planes reach the surface but do not root into any significant faults at depth. Consequently, traditional geologic approaches to seismic risk evaluation which rely largely on surface data are subject to numerous pitfalls when applied to fold and thrust belts.

Our interpretation of the structural style that developed in central California during the late Cenozoic requires that the strain associated with the transpressive motion between the Pacific and North American plates be resolved into normal and tangential components: thrust faulting and folding normal to the plate boundary and strike-slip faulting parallel to the plate boundary (San Andreas fault). The thrust faults root in a décollement at the brittle-ductile transition zone above which shortening is associated with folding and thrust faulting and beneath which shortening in the lower crust is accommodated by ductile processes of tectonic thickening or incipient subduction.

*Present address: 3937 Roderick Road, Los Angeles, California 90065.

INTRODUCTION

The Coalinga and Avenal earthquakes (M = 6.7, May 2, 1983, and M = 5.5, August 15, 1985, respectively) and their subsequent aftershocks have resulted in new attempts to understand the origin of active deformation along the west and south sides of the San Joaquin Valley (Figs. 1 and 2). The main shocks for both earthquakes occurred in close proximity to late Cenozoic folds and have similar hypocenter depths (10 km for Coalinga and 11.9 km for Avenal) and fault-plane solutions (northwest strike with either a steep northeast dip or a shallow southwest dip; Eaton and others, 1983; Eaton, 1985a, unpub. data; Fig. 2). Although both earthquakes occurred below large surface anticlines, the location and nature of their causative faults has remained enigmatic. No major faults are recognized at the surface or in the shallow subsurface in the epicentral areas (Dibblee, 1971; Kaplow, 1945), and only one case of minor ground rupture has been reported with an aftershock of the Coalinga event (Clark and others, 1983; Rymer and others, 1983). Spirit-leveling surveys of benchmarks in the Coalinga area, between 1972 and after the 1983 Coalinga earthquake sequence, however, show surface tilting which suggests active deformation at depth (Stein, 1983).

The structural model most frequently cited to explain the origin of late Cenozoic deformation along the west side of the San Joaquin Valley is wrench faulting associated with the San Andreas fault system (Harding, 1976). A less commonly mentioned model invokes serpentinite diapirism (Oakeshott, 1968), possibly acting in partial response to convergent wrenching. Explanations for the seismicity in the Coalinga-Avenal area include wrench faulting associated with the San Andreas fault (Fuller and Real, 1983), high-angle reverse faulting (Stein, 1983), blind thrusting (Namson and others, 1983), and flexural-slip faulting (Hill, 1984). In this paper, we use a variety of geological and geophysical data to constrain a structural model which uses thrust faults to explain the late Cenozoic folding and recent seismicity. Using this model as a guide, we present a new interpretation of the origin of late Cenozoic folds and faults along the west side of the San Joaquin Valley and place this interpretation into a regional framework consistent with recently published plate motions. Finally, we discuss the implications of the thrust-belt structural styles on earthquake hazard studies in the central Coast Ranges of California.

GEOLOGIC SETTING OF THE COALINGA-AVENAL AREA

The Coalinga-Avenal area lies along the eastern edge of the central Coast Ranges of California, bounded on the west by the San Andreas fault and on the east by the San Joaquin basin (Fig. 2). The stratigraphy of the

Geological Society of America Bulletin, v. 100, p. 257–273, 15 figs., February 1988.

Coalinga-Avenal area is well known from many previous studies (Woodring and others, 1940; Payne, 1962; Adegoke, 1969; Dibblee, 1971; Bate, 1984) and from numerous oil and gas exploration wells drilled in the area. The stratigraphic section consists of a thick sequence of Cretaceous through Quaternary strata depositionally overlying basement composed of the Coast Range Ophiolite (Hopson and others, 1981) and the Franciscan Assemblage (Page, 1981). East of the Coalinga-Avenal area and along the axis of the San Joaquin basin, drilling shows that the Cretaceous through Cenozoic section is nearly continuous; however, in the Coalinga-Avenal area, surface and subsurface data show that the section is interrupted by several unconformities of Tertiary and Quaternary age (Figs. 2 and 3) which are important features in interpreting the tectonic history of the area.

Stratigraphy

The stratigraphic relationships in the Coalinga-Avenal area reflect a complex depositional and tectonic history. It is not within the scope of this paper to discuss these relationships in detail, and the interested reader should refer to Namson and others (in press) for a more thorough review. These stratigraphic relationships have been used to divide the section into tecto-stratigraphic facies that bracket the major tectonic events and provide the basic stratigraphic elements used in structural analysis of the Coalinga-Avenal area (Fig. 3).

The structurally lowest rock unit in the Coalinga-Avenal area is the Jurassic and Cretaceous Franciscan Assemblage (KJf facies), which is tectonically overlain by the Coast Range Ophiolite along the Coast Range thrust (Hopson and others, 1981; Page, 1981). The Great Valley Group (Kgv facies) depositionally overlies the Coast Range Ophiolite and consists of as much as 8 km of Cretaceous to Paleocene marine strata (J. Q. Anderson, unpub. data; Payne, 1962). A disconformity exists between the lower and upper portions of the Great Valley Group (COSUNA, 1984).

A major regional unconformity (disconformity or very low-angle unconformity in the Coalinga area) separates the Kgv facies from the lower Tertiary marine strata of the Tk facies (Figs. 2 and 3; Nilsen and McKee, 1979). The Tk facies is composed of Paleocene to lower Eocene marine rocks of the Lodo Formation, Domengine Sandstone, and Kreyenhagen Formation (Mallory, 1959; Foss and Blaisdell, 1968; Addicott, 1972). In places, the entire Tk facies has been removed by erosion, and the overlying Ttm facies rests directly on pre–Tk facies rocks (see I, Fig. 2). Within the Coalinga area and along the margins of the San Joaquin Valley, this unconformity is angular. The Ttm facies consists of a variety of units, including the Temblor, Big Blue, Santa Margarita, Monterey (McClure Shale), and Reef Ridge Formations (Figs. 2 and 3).

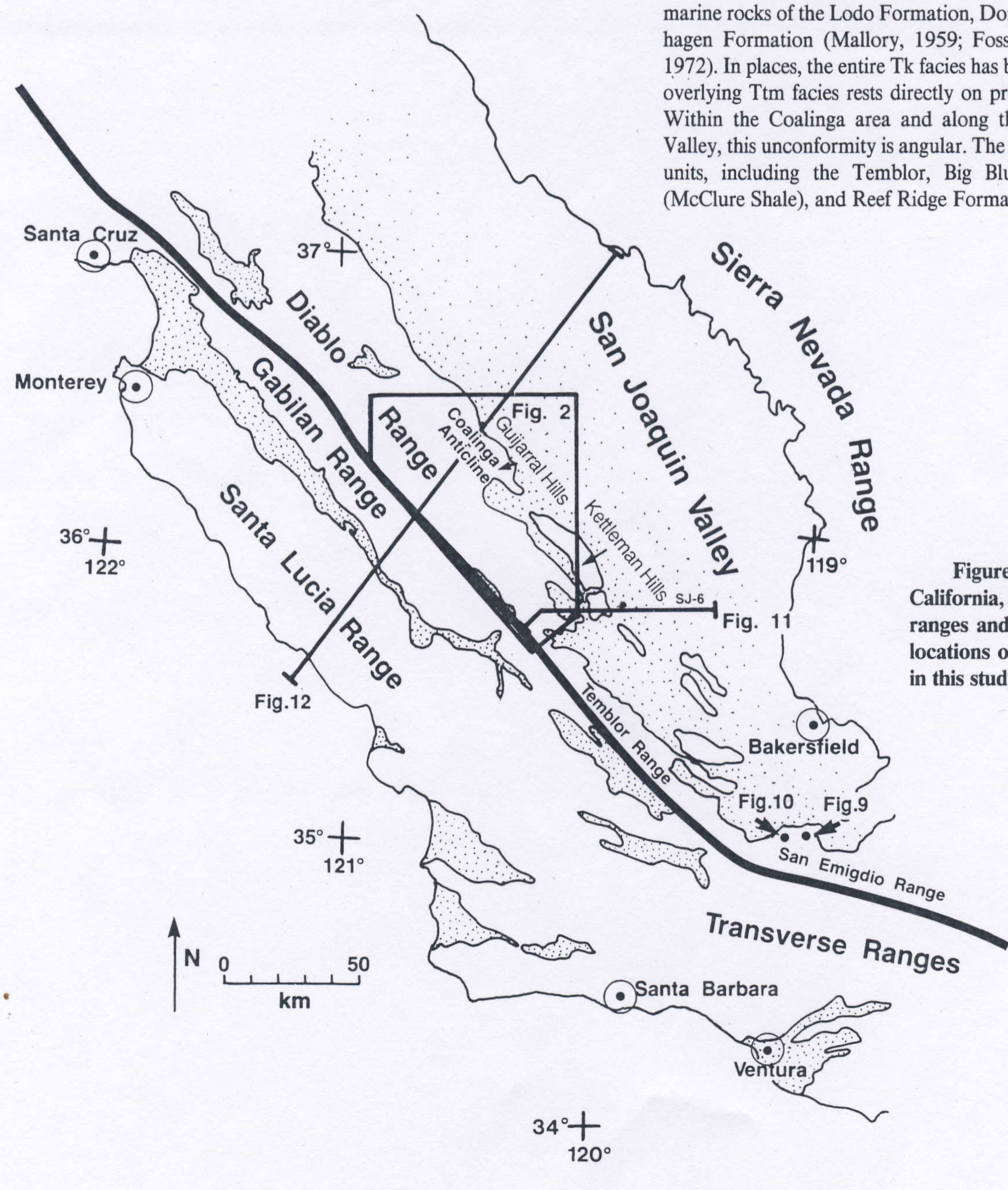


Figure 1. Geographic map of central California, showing the modern mountain ranges and valleys (stippled regions) and locations of areas shown in other figures in this study.

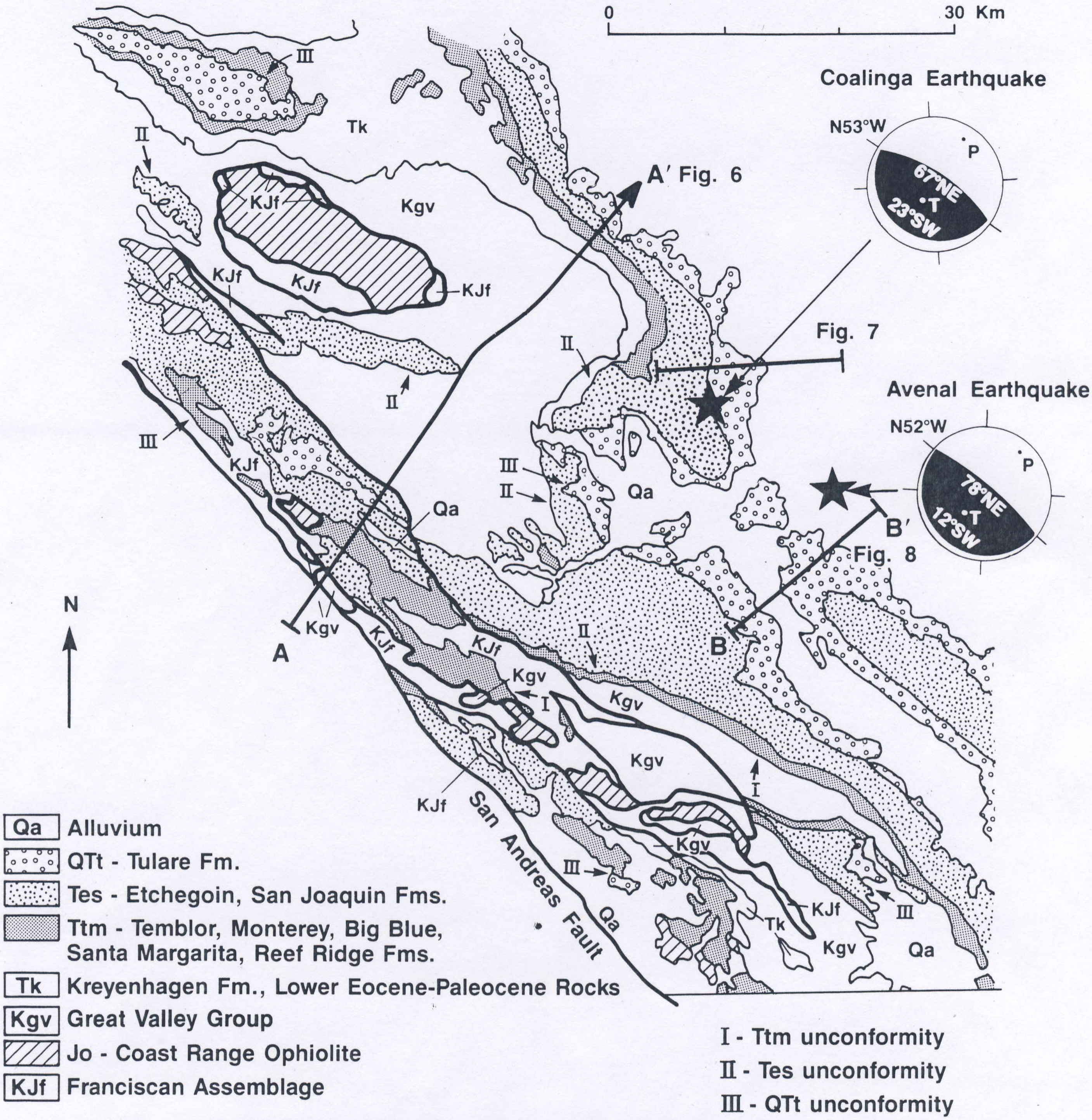


Figure 2. Geologic map of the Coalinga-Avenal area (modified from Jennings and Strand, 1958). Included on the map are the locations of structural cross sections A–A′ and B–B′ and a seismic reflection profile (Figs. 6, 8, and 7, respectively). Epicenters (stars) and fault-plane solutions of the Coalinga and Avenal earthquakes are from Eaton and others (1983) and J. P. Eaton (unpub. data). Roman numerals I, II, and III show locations of major angular unconformities between the tecto-stratigraphic facies.

The upper Cenozoic deposits in the Coalinga-Avenal area have been combined into the Tes facies (Etchegoin and San Joaquin Formations) and QTt facies (Tulare Formation and undifferentiated Quaternary alluvial deposits). In the Coalinga-Avenal area, the Tes facies overlies and onlaps the Ttm and older facies with an angular discordance of as much as 30° (see II, Fig. 2). The Tes facies consists of upper Miocene and Pliocene shallow-marine to nonmarine siltstone and sandstone (Repenning, 1976). In the Coalinga-Avenal area and throughout the western and southern San Joaquin Valley, the QTt/Tes facies contact ranges from being conformable along the basin axis to being an angular unconformity along the basin

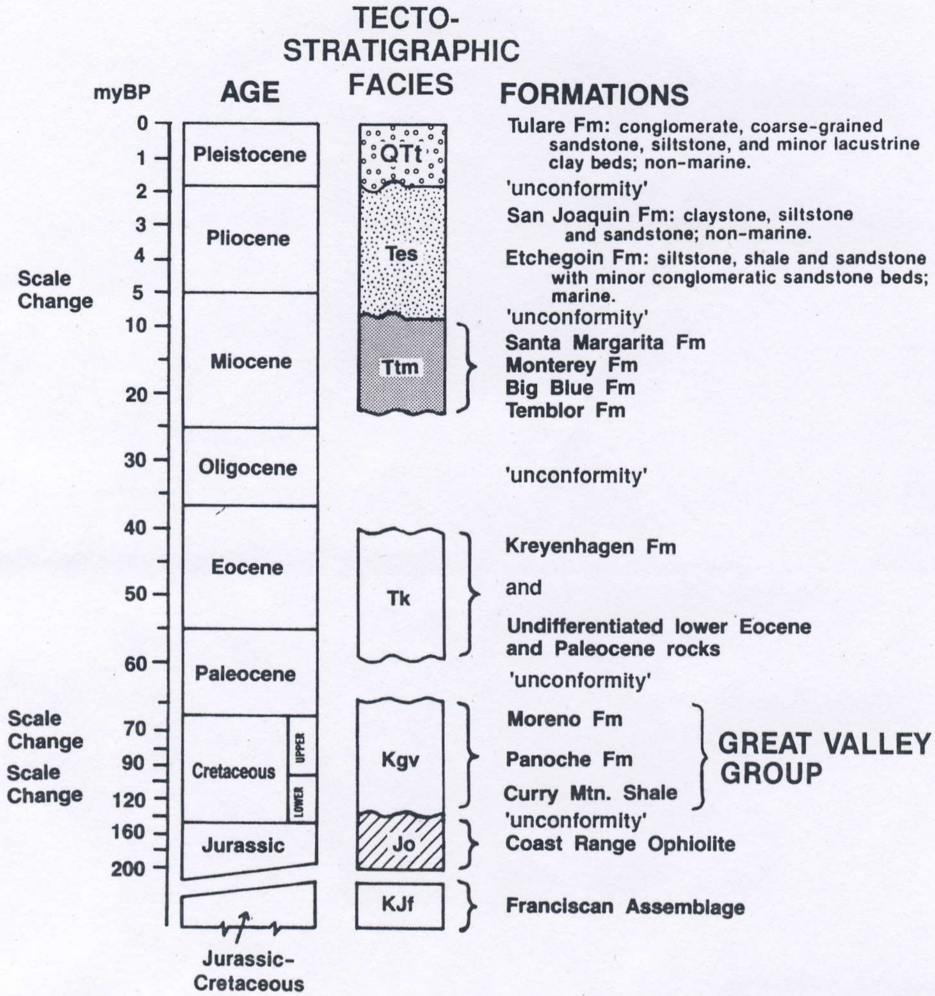


Figure 3. Stratigraphy of the Coalinga area. Stratigraphic correlation with the numerical time scale is derived from intercalibration of biozonations, radiometric dates, and the paleomagnetic time scale. The formations are grouped into tecto-stratigraphic facies that bracket the major tectonic events of the Coalinga-Avenal area (modified from Namson and others, in press).

margin (see III, Fig. 2; Foss, 1972). The fine-grained strata of the Tes facies coarsens upward to the QTt facies, which consists of upper Pliocene and Quaternary (<2.2 Ma, COSUNA, 1984) fluvial and alluvial-fan deposits with restricted occurrences of lacustrine beds (Fig. 3; Foss, 1972).

Structure

Published geologic maps of the Coalinga-Avenal area show that the structure is composed of northwest-trending folds that are subparallel to or at low-angle intersection with the San Andreas fault (Fig. 2; Dibblee, 1971). In the Coalinga-Avenal area, the structural relief and dips are moderate on the anticlines along the west margin of the San Joaquin basin, but deformation increases westward into the Diablo Range. The Coalinga anticline is the northernmost fold in a long line of anticlines that include the Guijarral Hills anticline and the Kettleman Hills North Dome, Middle Dome, and South Dome anticlines. This line of folds forms a topographic break between the San Joaquin Valley and the Diablo Range (Fig. 1). All of these folds are broken in places by minor faults (<100 m of displacement) at the surface, but no major faults in the surface or shallow subsurface have been recognized that separate these structures from the relatively undeformed strata in the San Joaquin Valley (Dibblee, 1971 and 1973). These folds are considered geologically young or active because they lie above a zone of recent seismicity, they deform sediment at least as young as mid-Pleistocene in age (Dibblee, 1973; Page, 1985), and recent geodetic surveys suggest active tilting and uplift (Stein, 1983). Although these folds are characterized by young deformation, surface and subsurface data show that some of the folds, especially those within the Diablo Range, are the result of multiple deformations.

Multiple phases of deformation during the Cenozoic are documented in the Coalinga area by geologic relationships such as angular unconformities and locally derived, coarse-grained units that are interpreted to be synorogenic deposits (Namson and others, in press). The oldest tectonic event is documented by a major disconformity between the Kgv and Tk facies. The time gap represented by this disconformity is the Paleocene, which is in part coincident with the suggested time of emplacement of the Coast Range thrust (Page, 1981). The disconformity may be associated with movement of the Coast Range thrust. Although there is little or no angular discordance along this unconformity at the Coalinga anticline, the disconformity occurs along the entire length of the west and south sides of the San Joaquin Valley, and in places, there is a significant angular unconformity (Dibblee, 1971 and 1973).

The geometry of the basal Ttm facies unconformity and provenance studies within this sequence (Bate, 1984) suggest that the Coalinga anticline began deforming prior to and during initial Ttm facies deposition (Oligocene to early Miocene) in response to a phase of mid-Cenozoic tectonism. The basal Ttm unconformity is not restricted to the Coalinga area but is observed all along the south and west sides of the San Joaquin Valley (Bandy and Arnal, 1969; Nilsen and others, 1973; Dibblee, 1973; Davis and Lagoe, 1984). In detail, this unconformity is time-transgressive and may span the entire Oligocene (COSUNA, 1984), and there are also a

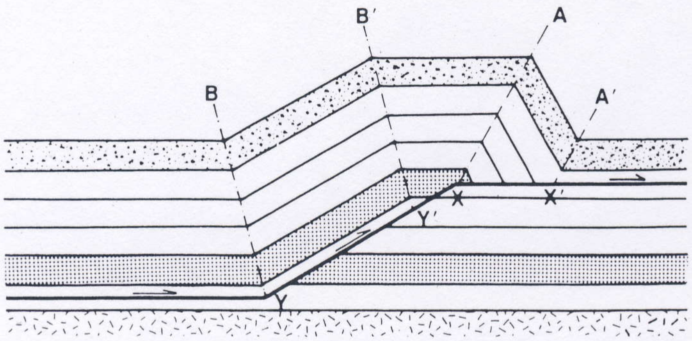


Figure 4. Anticline caused by fault-bend folding as a thrust sheet is translated over a nonplanar fault. The front limb (A'–A') forms as the hanging-wall cutoff (X'–Y') is translated from the ramp (X–Y) onto the upper bedding-plane thrust. The back limb (B–B') forms as the hanging wall is translated up the ramp (after Suppe and Namson, 1979).

number of local unconformities within the Ttm facies. The large areal extent of the basal unconformity suggests that the mid-Cenozoic tectonism was a regional event affecting the Coast Ranges with deformation intensity diminishing eastward into the San Joaquin Valley (Namson and Davis, 1984; Davis, 1986).

The angular unconformity at the base of the Tes sequence is present along the west and south sides of the San Joaquin Valley and within the Diablo and Temblor Ranges (Christensen, 1965; Dibblee, 1971, 1973). We believe that the shallow-marine to nonmarine rocks of the Tes facies were deposited on the erosional remnants of structures formed during mid-Cenozoic tectonism. Deposition of the Tes facies thus postdates the mid-Cenozoic tectonism and represents a period during which little or no structural relief developed in the Coalinga-Avenal area.

The most recent and seismically active phase of uplift and deformation of the Coalinga-Avenal area is documented by the unconformity along the basin margin between the QTt facies and the Tes facies. The QTt facies is composed of synorogenic deposits laid down during the past 2–3 m.y. in response to the late Cenozoic uplift and erosion of the Coalinga-Avenal area and nearby Coast Ranges (Christensen, 1965; Namson and others, in press).

FOLD MODELS

One of the goals of this paper is to determine the origin of late Cenozoic folding and recent seismicity along the San Joaquin Valley margin. This folding is generally considered to be the result of wrench tectonics associated with the San Andreas fault (Harding, 1976; Page, 1981). In the model, the wrench folds are located adjacent to strike-slip faults and are associated with subsidiary oblique-slip faults that steepen with depth. This characteristic geometry is commonly referred to as a "flower structure." There are numerous problems, however, in applying the wrench-tectonics model to explain the folds of the San Joaquin Valley.

(1) The folds are as much as 40 km away from the San Andreas fault, and, to the best of our knowledge, surface mapping (Dibblee, 1973, 1971) and subsurface drilling show that significant oblique-slip faults have not been encountered near the folds. The lack of oblique-slip faults led Harding (1976, p. 371) to postulate that these folds may be due to convergence.

(2) If the San Andreas fault or associated faults are the cause of the folds, then the structural histories of the two features should be closely related. According to wrench-fault principles (Wilcox and others, 1973), folding should have developed during the early stages of strike-slip displacement, which is late middle Miocene time (12 Ma; Crowell, 1979), and terminated as the principal strand of the San Andreas fault developed. As discussed above, deposition of the synorogenic QTt facies (<2.2 Ma; COSUNA, 1984) suggests that the late Cenozoic deformation is <3 Ma and is still developing as evidenced by the recent earthquakes and topographic uplift (Stein, 1983). Harding (1976) pointed out that there are folds of middle to late Miocene age which are synchronous with the initiation of displacement on the San Andreas fault. These folds, however, are of limited distribution and relatively small structural relief. Regional maps (Dibblee, 1973) and subsurface studies (Division of Oil and Gas, 1982) show that the late Cenozoic (<2.2 Ma) folding is more widely distributed and of much greater structural relief than are the Miocene folds. The age discrepancy between the late Cenozoic folding and initiation of the San Andreas fault suggests that the recent folds are not related to the wrench-tectonics model.

(3) Fault-plane solution studies of the recent Coalinga and Avenal earthquake sequences show that the main shocks and significant aftershocks yield either high-angle reverse fault or low-angle thrust fault solutions. Oblique-slip motion on faults would be expected if the folds are related to wrench faults (Lowell, 1972; Sylvester and Smith, 1976).

Our analysis of the structural geometry and seismicity of folds in the Coalinga-Avenal area and other examples suggests that folds along the west margin of the San Joaquin basin can be related to thrust faults that do not reach the surface (blind thrusts). The geometry and origin of the structures can be satisfactorily explained as either fault-bend folds (Fig. 4), wherein a fold forms in the hanging-wall sheet as it moves over a bend in a fault (Suppe and Namson, 1979; Suppe, 1983), or fault-propagation folds (Fig. 5), wherein an anticline forms above a propagating thrust fault (Suppe and Medwedeff, 1984). Both fold styles are commonly observed in fold and thrust belts, and the models illustrate how fault and fold shape are intimately related.

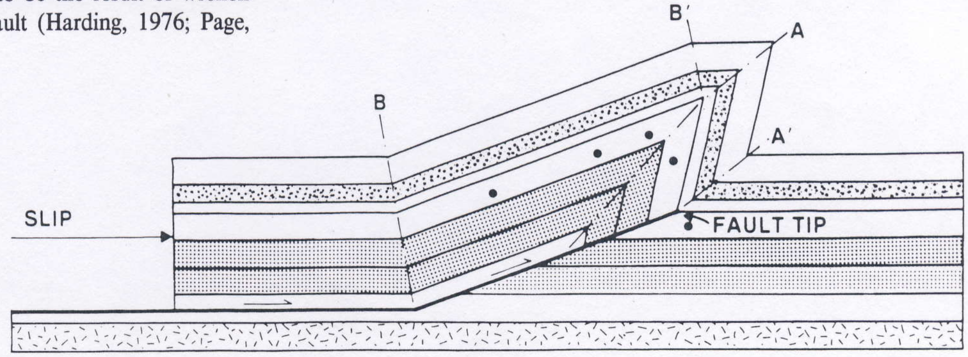


Figure 5. Anticline caused by fault-propagation folding. The bedding-plane thrust cuts across section, and a fold forms with the synclinal axis terminating at the propagating fault tip. Fault slip progressively decreases to zero at the tip of the propagating fault (after Suppe and Medwedeff, 1984).

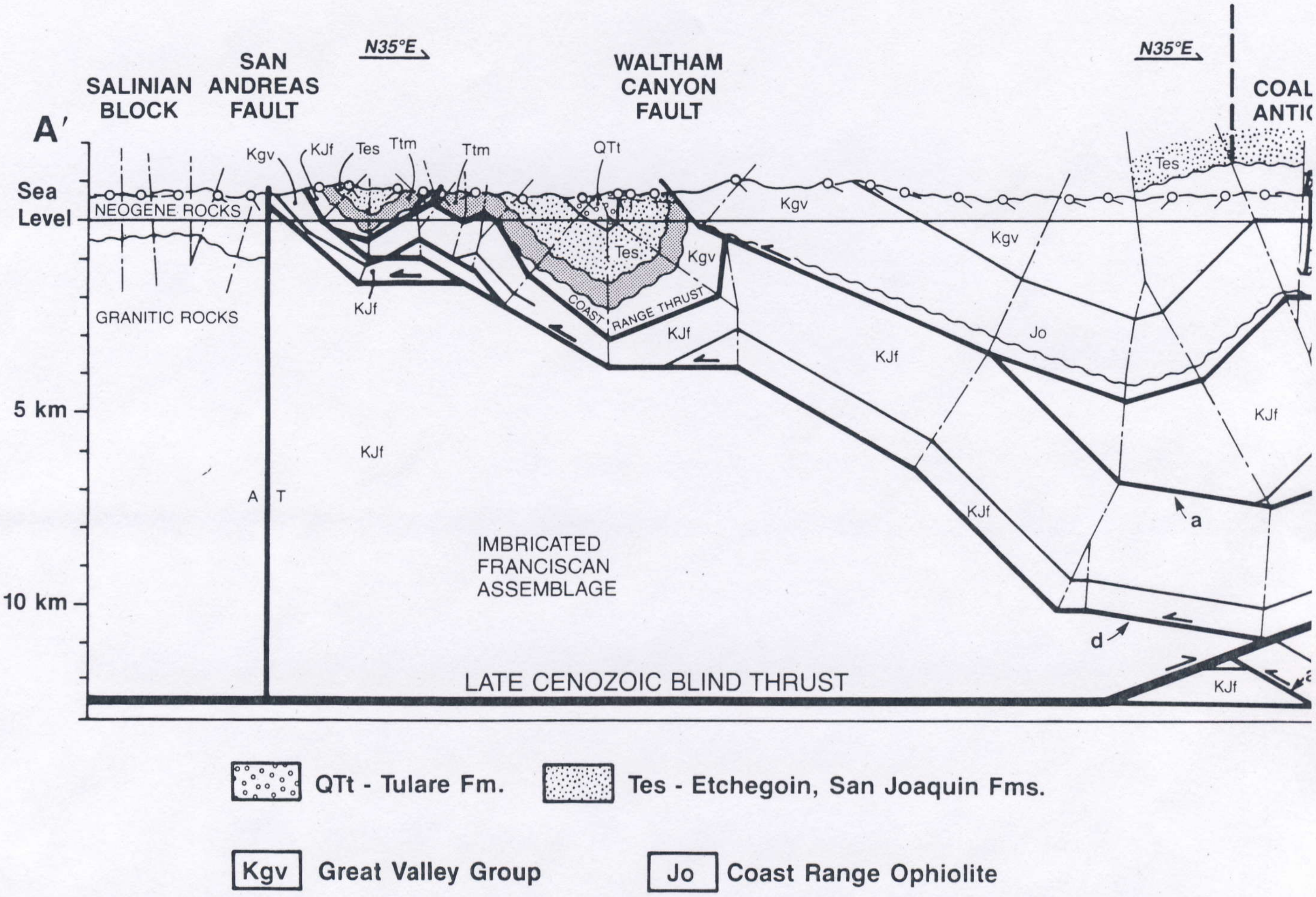


Figure 6. Geologic cross section A–A′ (after Namson and others, in press; see Fig. 2 for location). This solution illustrates the low-angle thrust geometry and multi-phase deformations in the Coalinga area. We interpret the late Cenozoic fold and May 2, 1983, Coalinga earthquake to be associated with the blind thrust. (Note overlap in center.)

STRUCTURAL SOLUTION FOR THE COALINGA AND KETTLEMAN NORTH DOME ANTICLINES

The structural interpretation for the Coalinga and Kettleman North Dome anticlines and Coalinga and Avenal earthquakes is primarily based on construction of kinematically restoreable cross sections. Namson and others (in press) have discussed the stratigraphic and structural relations that suggest that the Coalinga area has been affected by two deformations, one during the Oligocene and one during the late Pliocene to present. Evidence for the mid-Cenozoic deformation includes erosion of 6–7 km of Upper Cretaceous strata west of the Waltham Canyon fault (see I, Figs. 2 and 6) and the presence of a late Miocene unconformity (angular in places) where the Tes facies is deposited over older units across the Coalinga anticline (Figs. 2 and 6). Varying structural relief for different stratigraphic units within the Coalinga anticline indicates about 4.2 km of mid-Cenozoic structural relief and 2.5 km of late Cenozoic structural relief (see Fig. 6).

In our interpretation of the structural styles for these events, the mid-Cenozoic deformation was caused by a west-directed fold and thrust belt, whereas the late Cenozoic deformation and seismicity are caused by an active east-directed fold and thrust belt (Namson and Davis, 1984; Namson and others, in press). In this paper, we consider only the geometry of the late Cenozoic structures and their implications for uplifting the present-day southern and central Coast Ranges.

Late Cenozoic formation of the Coalinga anticline is interpreted as the result of motion on a major thrust that ramps up to the east from about 12.5 to 8 km depth (Fig. 6). There are several lines of evidence that support the proposed geometry, location, and sense of displacement on this fault.

(1) The structural interpretation explains the origin and geometry of the fold observed at the surface and in the subsurface. The east limb of the Coalinga anticline is related to eastward movement of the hanging-wall cutoff onto the higher décollement of the late Cenozoic thrust (Fig. 6), generating a frontal limb of a fault-bend fold. As the hanging wall is

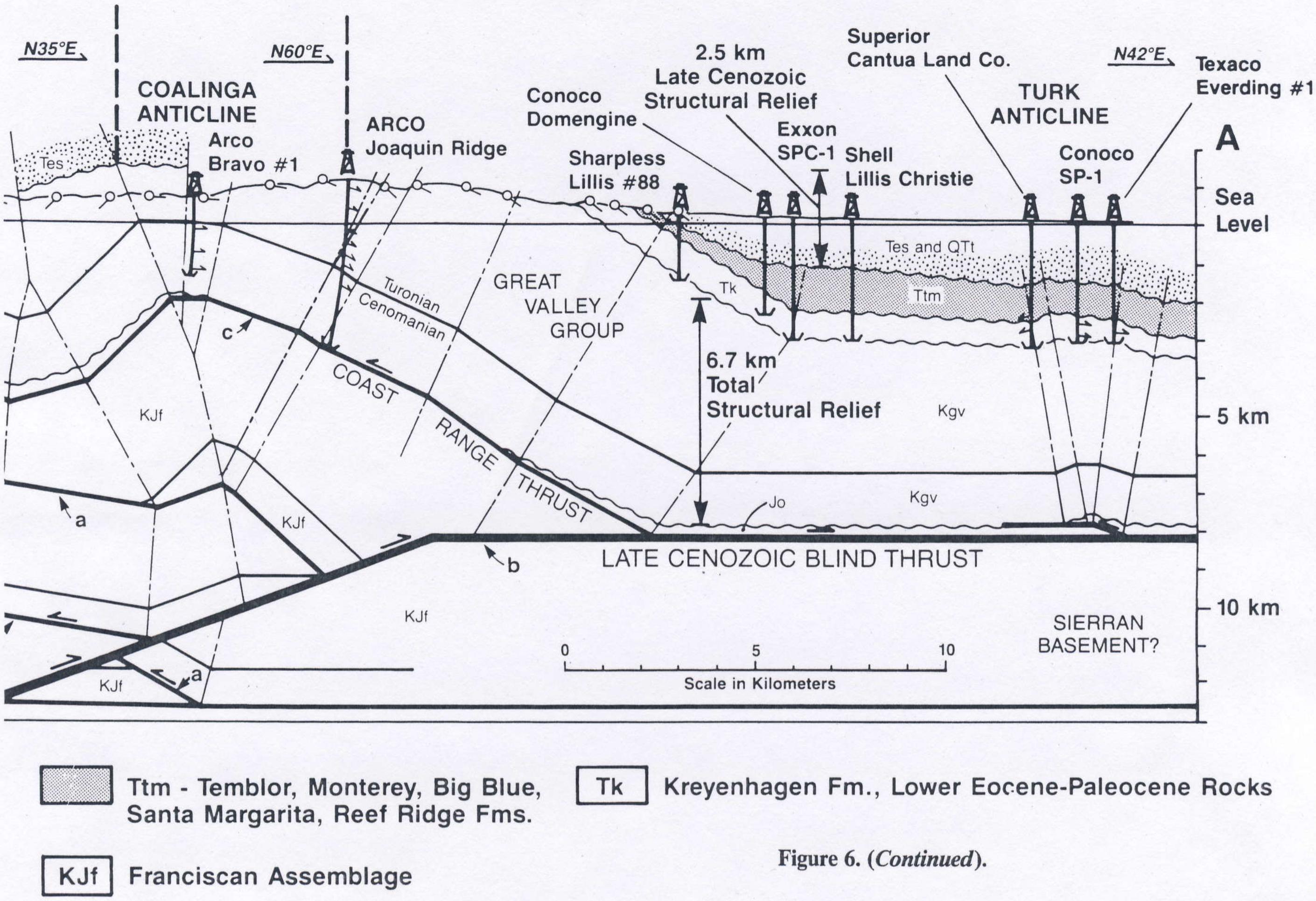


Figure 6. (*Continued*).

translated up the thrust ramp, the west limb (or back limb) of the Coalinga anticline is folded, and strata older than the Tes unconformity are refolded. Strata below the Tes unconformity were originally folded by mid-Cenozoic movement on fault a (Fig. 6).

(2) The geometry of this interpretation is also consistent with seismic reflection data (Fig. 7). A seismic reflection profile across the east limb of the Coalinga anticline and located several kilometres south of the cross-section line shows east-dipping reflectors terminating downward into flat reflectors at about 4.3 sec. This discordance is believed to be due to a flat thrust fault overlain by an east-dipping hanging-wall cutoff section and underlain by a relatively flat-lying footwall section. Both hanging-wall and footwall reflectors are most probably from the Franciscan Assemblage, which is both bedded and foliated in the central Coast Ranges (Page, 1981).

(3) Initial seismological studies of the main Coalinga earthquake and aftershocks support the presence of a thrust fault (Eaton and others, 1983; O'Connel and Murtha, 1983). These studies show that the locations of the main shock and aftershocks define a low-angle, southwest-dipping plane that is consistent with the low-angle fault-plane solution derived for the main shock. In a more detailed analysis, Eaton (1985a) argued that seismicity on several faults may be necessary to explain the distribution and orientation of the more than 100 earthquakes studied, although he concluded that the sum of the evidence strongly favors the thrust-fault solution for the main shock. If the main shock is projected from its focus horizontally along regional strike into the cross section, it falls on the ramp segment of the postulated late Cenozoic thrust fault. We therefore suggest that movement along this fault may have been the source of the Coalinga earthquake. Movement on this thrust fault is responsible for generating 2.5 km of structural relief on the Coalinga anticline during the late Cenozoic (Fig. 6).

The geometry of the thrust-fault interpretation requires the continuation of about 6 km of slip eastward into the San Joaquin Valley along a blind thrust fault, and this amount of slip must be accounted for by shortening in the overlying thrust sheet. Our interpretation shows that this slip can be absorbed in west-directed "back" thrusts, such as the fault responsible for Turk anticline and the Waltham Canyon fault (Fig. 6). The back thrust responsible for Turk anticline is also a blind thrust; however, back thrusting along the Waltham Canyon fault reaches the surface and deforms upper Cenozoic deposits. The second-order folds observed on the seismic reflection profile are also interpreted to be the result of back thrusting along the upper detachment (Fig. 7).

The structural interpretation for Kettleman Hills North Dome anticline is based on subsurface-well information and surface geologic maps (Figs. 2 and 8). These data show that the anticline has a broad subhorizontal crest with symmetrical limb dips of about 20°. Detailed geologic map-

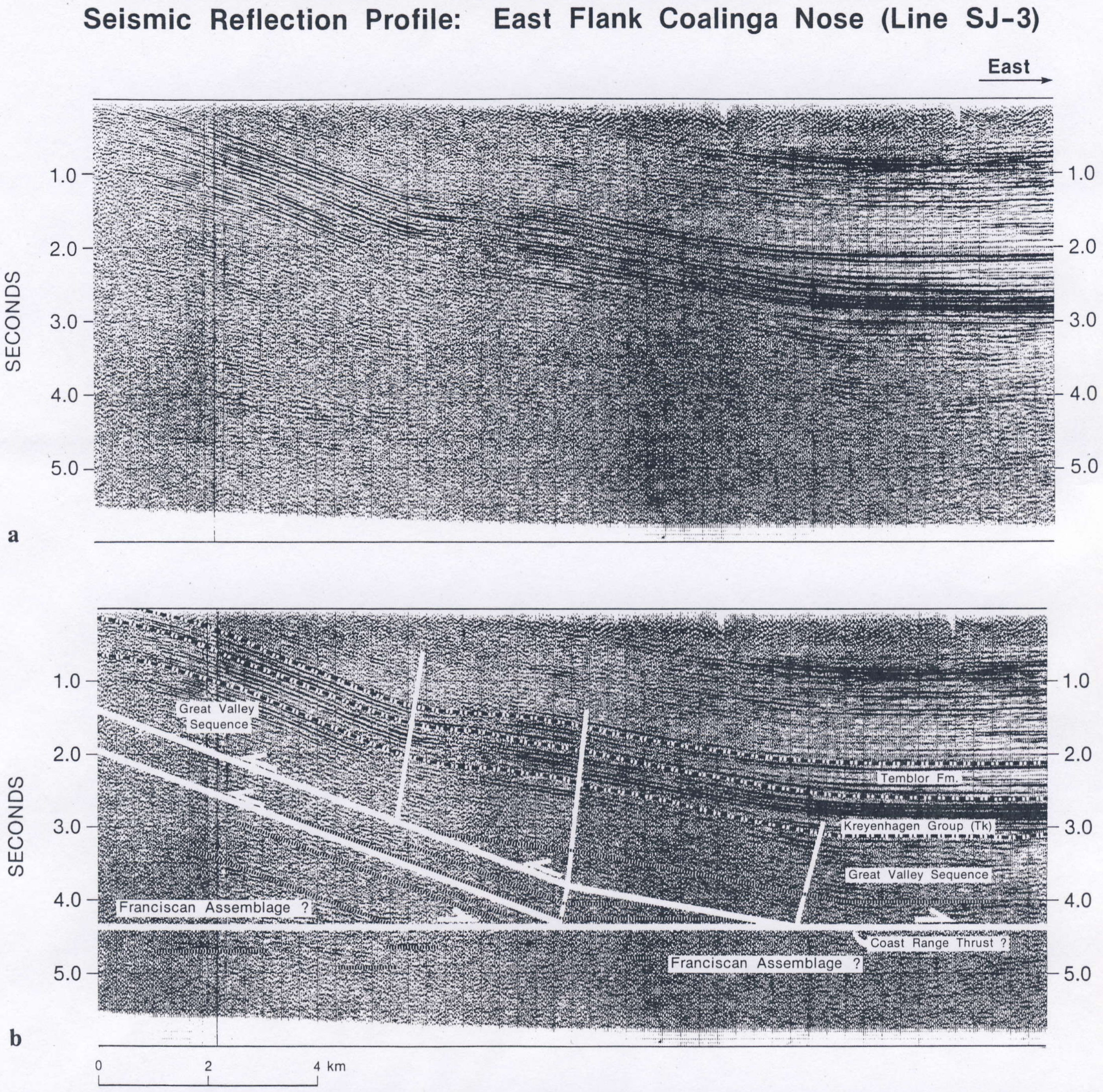


Figure 7. Seismic reflection profile through the east limb of the Coalinga anticline (see Fig. 2 for location). The low-angle thrust geometry is illustrated by the downward termination of east-dipping reflectors into flat reflectors at about 4.3 sec. The structural complexity of the east limb is the result of a back thrust.

ping by Woodring and others (1940) shows the crest of the anticline to be cut by numerous steeply dipping small faults that are probably the result of local extension along the axis of the anticline. Cretaceous through Pliocene units are all equally deformed in the subsurface, indicating that folding is solely of late Cenozoic age. The structural relief along this cross section is 0.7 km and is calculated by comparing subsurface depths of stratigraphic units on the anticline crest with those in the San Joaquin Valley to the east. The cross section is across the northern end of the fold, and so the total structural relief on North Dome anticline is likely to be much greater to the south through its structural culmination.

The depth of the postulated thrust fault responsible for the North Dome anticline is not well constrained. The fault cannot be shallower than

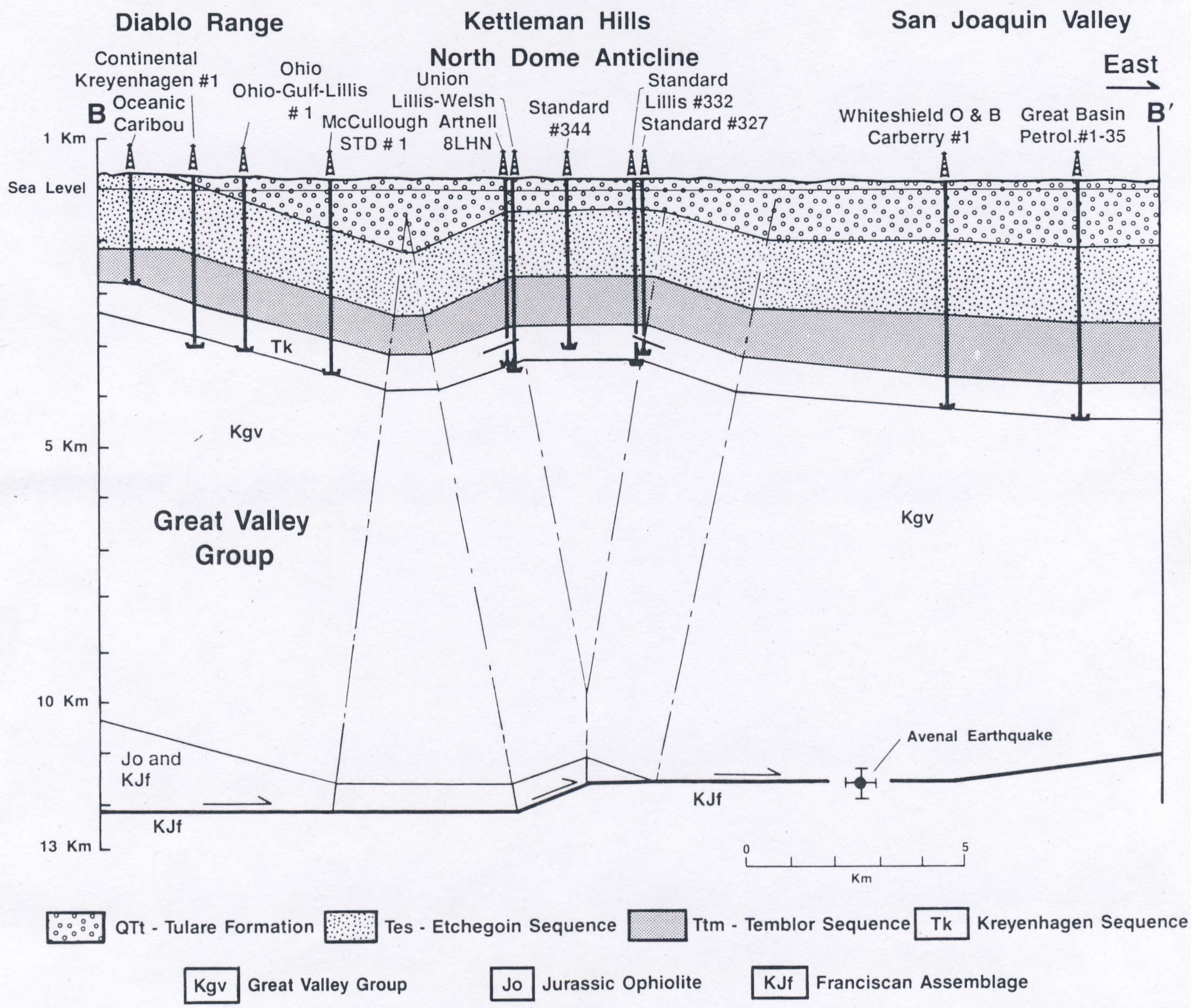
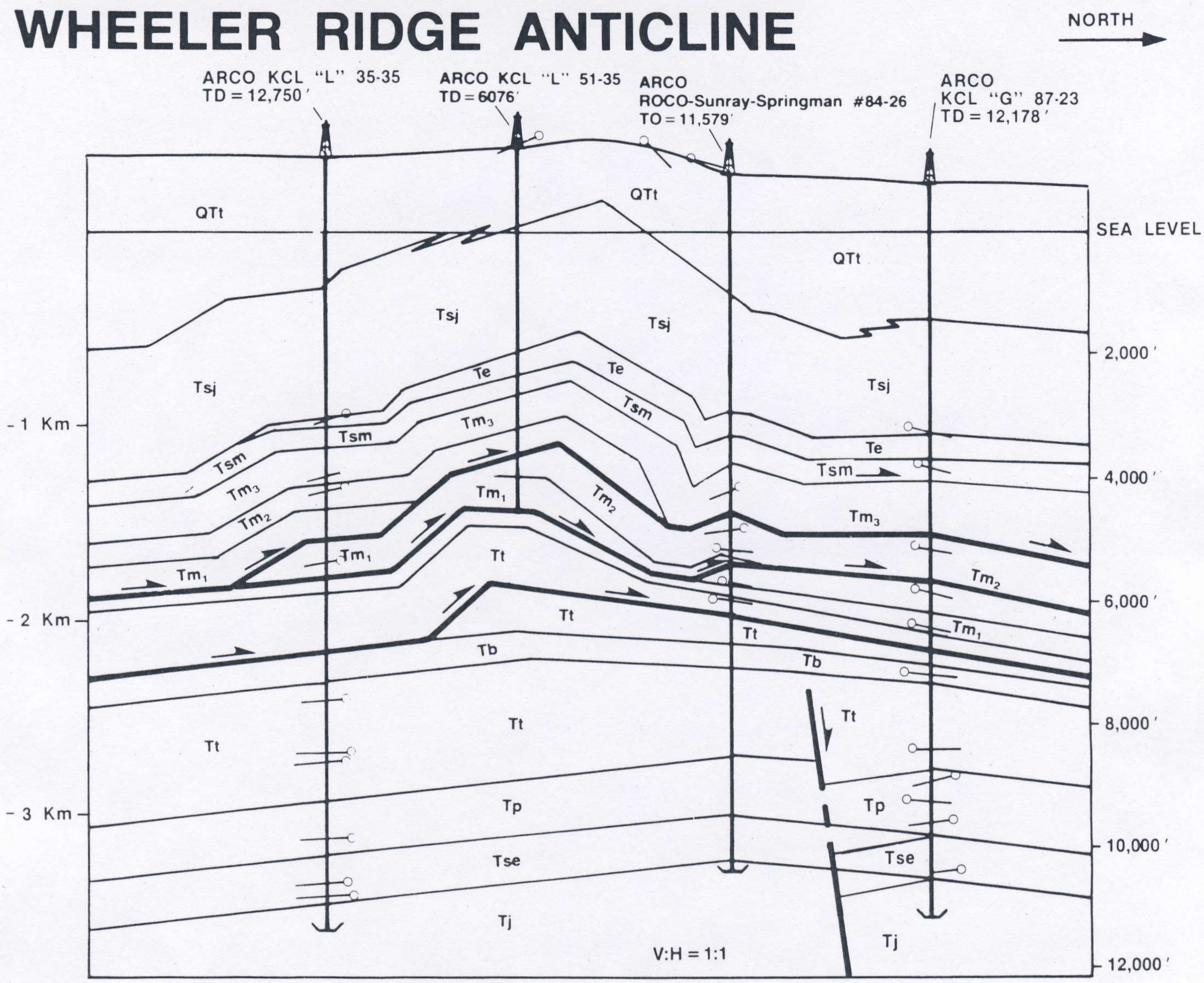


Figure 8. Geologic cross section B–B′ across the north plunge of Kettleman North Dome anticline (see Fig. 2 for location). The anticline is interpreted to be a fault-bend fold associated with a thrust for which the lower décollement is within the Franciscan Assemblage and which steps up to a higher décollement at the base of the Great Valley Sequence. The location of the August 15, 1985, Avenal earthquake is projected onto the section line (hypocenter information is from J. P. Eaton, unpub. data).

wells drilled in the area (<3.6 km) and the fold shape alone is insufficient to uniquely constrain the fault location. We can use information from the Avenal earthquake, analogy with the Coalinga area, and the fold geometry, however, to develop an internally consistent interpretation. As previously mentioned, a fault-plane solution for the Avenal earthquake suggests the presence of a southwest-dipping thrust or a northeast-dipping reverse fault. As in the case of the Coalinga earthquake, the thrust mode is favored for the Avenal earthquake because there was no indication of surface or shallow subsurface fault movement, and aftershocks define a southwest-dipping fault plane (J. P. Eaton, unpub. data). The Avenal earthquake occurred at a depth of 11.9 ± 0.3 km, which is interpreted to be the depth of the basement/sediment contact (J. P. Eaton, unpub. data). Similar depths to the basement/sediment contact are derivable from the COCORP seismic reflection profile through this area (Fielding and others, 1984). Projecting the hypocenter of the Avenal earthquake into the North Dome cross section therefore gives the approximate depth to basement (base of Great Valley Group) and position of the thrust fault (Fig. 8). By analogy with the Coalinga area, the basement/sediment contact is the position of the higher décollement of the fault-bend fold. If we combine the position of the higher detachment and the observed fold geometry, then the principles of fault-bend folding can be applied to constrain the location and shape of the thrust ramp (Fig. 8). The fault slip is 2.7 km.



EXPLANATION

QTt: TULARE FM
(Plio-Pleistocene)

Tsj: SAN JOAQUIN FM AND CHANAC FM
(Pliocene)

Te: ETCHEGOIN FM
(Upper Miocene)

Tsm: SANTA MARGARITA FM
(Upper Miocene, Upper Mohnian)

TM_3 MONTEREY FM
(Upper Miocene)

TM_2 MONTEREY FM
(Lower most Upper Miocene - Middle Miocene)

TM_1 MONTEREY FM
(Lower Miocene)

Tt: TEMBLOR FM
(Olig-Miocene)

Tb: BASALT, DACITE, RHYOLITE
(Olig-Miocene)

Tp: PLEITO FM
(Oligocene)

Tse: SAN EMIGDIO FM
(Eocene)

Tj: TEJON FM
(Eocene)

Jop: GABBRO AND SCHIST
(Jurassic?)

0 — 1 Km

Figure 9. Example of a thrust-related fold forming Wheeler Ridge at the south end of the San Joaquin Valley (see Fig. 1 for location; modified from Davis, 1983). Fold shape and low-angle thrust geometry are constrained by mapping and subsurface drilling. We interpret this fold to be several stacked fault-bend folds.

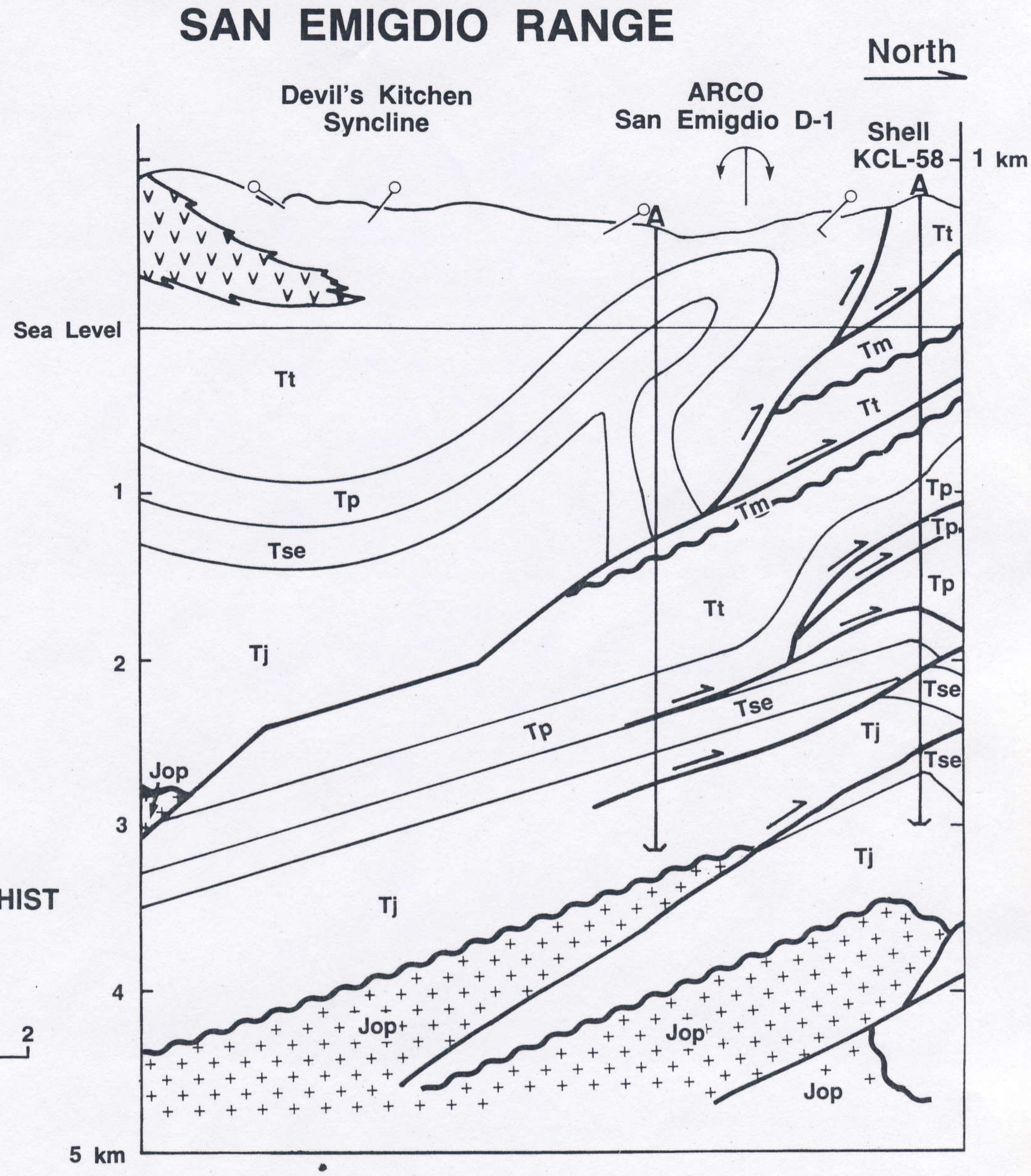


Figure 10. Example of a thrust-related fold in the San Emigdio Mountains (see Fig. 1 for location; modified from Davis, 1983). Geologic mapping and subsurface drilling constrain the fold and fault geometry. We interpret this fold to have formed initially as a fault-propagation fold and to have been subsequently translated northward as a fault-bend fold.

STRUCTURAL STYLE OF LATE CENOZOIC DEFORMATION ALONG THE WEST AND SOUTH SIDES OF THE SAN JOAQUIN VALLEY

Inspection of published surface maps and cross sections along the west and south margins of the San Joaquin Valley suggests that other late Cenozoic folds are undergoing deformational processes similar to those presented for the Coalinga-Avenal area. Geophysical data and data from oil and gas exploration wells indicate that many of these folds occur in the upper plates of thrust faults and can also be interpreted as either fault-bend folds or fault-propagation folds.

The Wheeler Ridge anticline, at the southern end of the San Joaquin Valley, is interpreted to be a fault-bend fold (Figs. 1 and 9). The structure is well constrained by surface mapping and subsurface drilling to be a large, east-plunging, north-vergent anticline that has uplifted the ridge during the Quaternary (Hoots, 1930; Davis, 1983). Abundant well data from the Wheeler Ridge and North Tejon oil fields (Carls, 1951, 1955; Davis, 1983, 1986; Medwedeff, 1984) show that the anticline is underlain by a south-dipping set of thrust faults collectively called the "Wheeler Ridge thrust." Correlation of well data shows that the set of thrusts ramps up from the upper portion of the Temblor Formation and the base of the Monterey Formation to the upper portion of the Monterey Formation. These data also show that biostratigraphic intervals within the Monterey Formation are repeated by the thrusts. Well penetrations north and south of Wheeler Ridge indicate that the thrusts become parallel to bedding away from the anticline. The geometry of the Wheeler Ridge thrusts and the Wheeler Ridge anticline strongly suggests that it is the result of fault-bend folding (Fig. 4). The numerous thrusts have produced a stacked set of anticlines with the structurally lowest being the youngest. Slip on the thrusts is believed to continue out into the southern San Joaquin Valley and be absorbed in subsurface folds, back thrusting (Davis, 1986), and possible compaction.

An anticline on the north limb of the Devils Kitchen syncline in the San Emigdio Mountains (Figs. 1 and 10) illustrates another example of thrust-related folding. Geologic mapping (Hoots, 1930; Dibblee, 1974) and oil exploration wells show that the anticline is asymmetric in shape, having a steep to overturned north limb (Fig. 10). The ARCO D-1 well near the crest of the anticline was drilled down the steep north limb of the

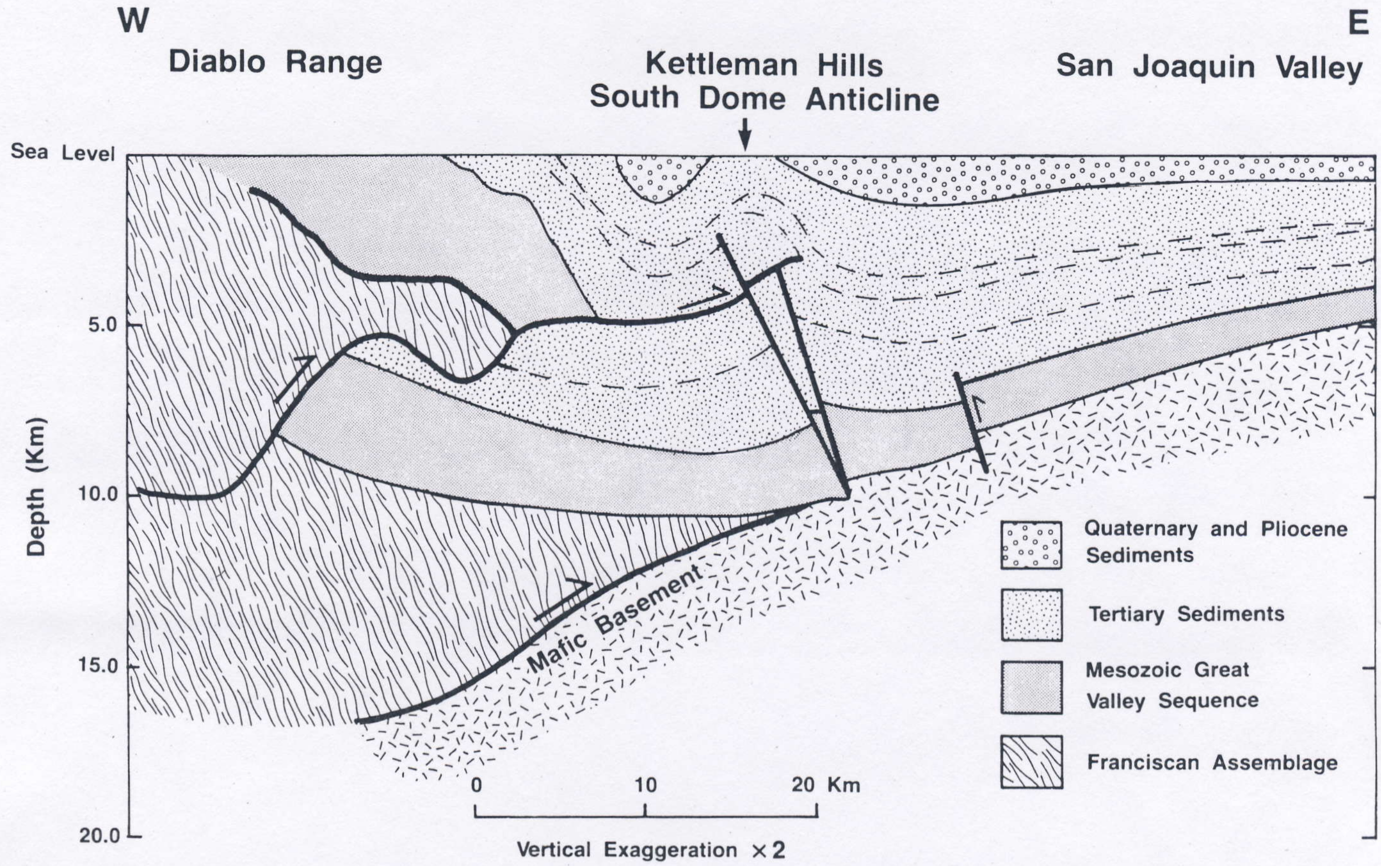


Figure 11. Example of a fault-propagation–fold interpretation for Kettleman South Dome anticline (see Fig. 1 for location; modified from interpreted seismic reflection profile SJ-6, Wentworth and others, 1983).

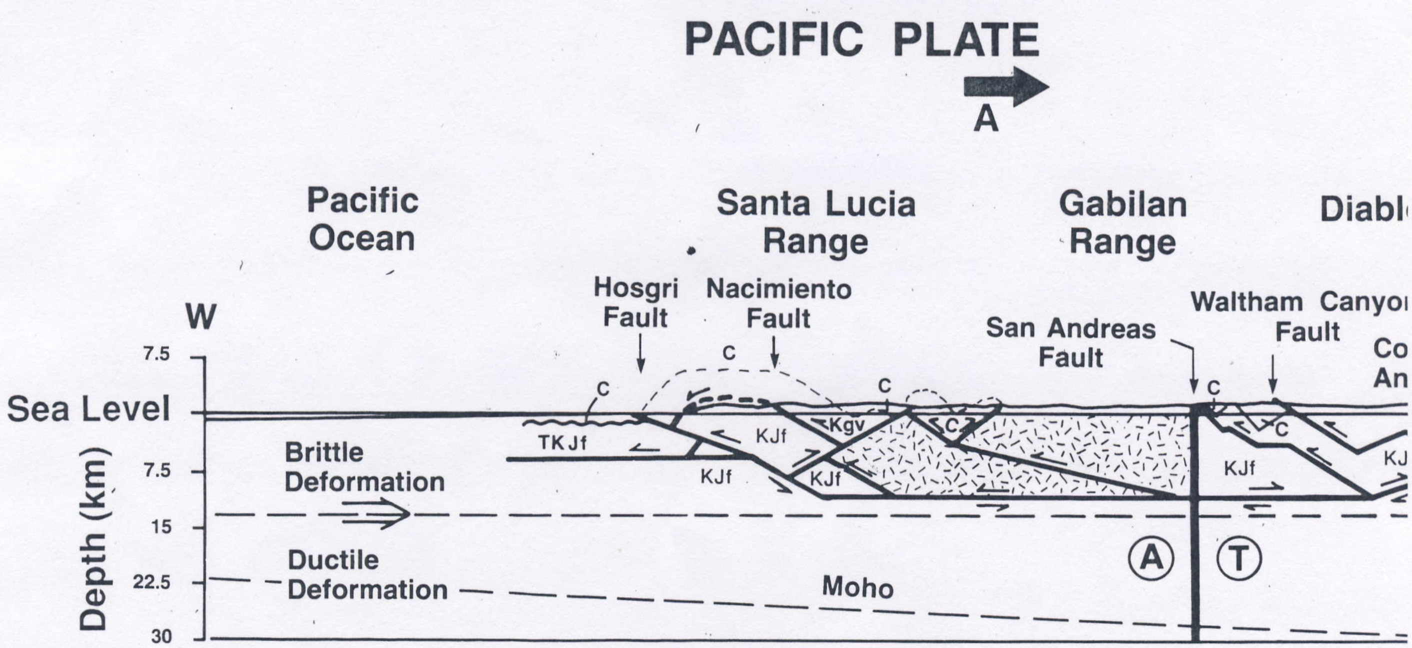


Figure 12. Geologic cross section illustrating a tectonic model for deformation across the North American/Pacific plate boundary (see Fig. 1 for location). Transpressive motion along the plate boundary is resolved into two strain components. One component is tangential to the plate boundary and is strike slip on the San Andreas fault. The other component is normal to the plate boundary and is compression on thrust faults and folds across the California Coast Ranges. Thrust faults root in the brittle-ductile transition zone, defined by the maximum depth of earthquakes, and shortening above this zone is accommodated by folding and faulting. Below the brittle-ductile transition zone, shortening occurs by ductile deformation processes or incipient subduction. (Note overlap in center.)

unnamed anticline until the Pleito thrust fault was crossed. Below the fault is a repeated Tertiary section which is dipping moderately to the south. The asymmetric and overturned fold geometry and the presence of an underlying thrust fault strongly suggest that the unnamed anticline formed initially by the process of fault-propagation folding and was subsequently transported northward on a through-going splay of the Pleito thrust system (Davis, 1983). It is possible that the fault-propagation fold was subjected to fault-bend folding in these later stages of thrust movement.

Another example of a thrust-related fold is South Dome anticline of the Kettleman Hills (Figs. 1 and 11). South Dome anticline is part of the southern extension of the line of anticlines along the west side of the San Joaquin Valley that starts at the Coalinga anticline. Wentworth and others (1983) interpreted a seismic reflection profile across this structure as showing eastward-vergent folding of late Cenozoic age above a west-dipping thrust fault that terminates in the syncline to the east (Fig. 11). Their interpreted geometry is similar to that of the model of a fault-propagation fold (Fig. 5) with fault slip decreasing eastward to zero below an asymmetric anticline having a steep east limb.

REGIONAL IMPLICATIONS

Our interpretation of the thrust-fault origin for the Coalinga and Kettleman Hills North Dome anticlines, 1983 Coalinga and Avenal earthquakes, and other selected examples of folds from the San Joaquin basin has important regional implications for the structure along the entire west side of the San Joaquin Valley, as well as the central Coast Ranges. Preliminary evaluation of surface maps and well data along the margin of the San Joaquin Valley indicates a deformed belt, >200 km in length, that contains many folds that deform Pliocene and Quaternary deposits. As previously stated, we interpret this deformation as an actively developing fold and thrust belt (Fig. 1).

Page and Engebretson (1984) enumerated several lines of geologic evidence that support development of compressional structures during the past 3 m.y. throughout the central Coast Ranges. These observations include (1) uplift of the Diablo, Santa Cruz, Gabilan, and Santa Lucia Ranges, all parallel to the San Andreas fault, (2) development of Quaternary folds parallel to, and both east and west of, the San Andreas fault, and (3) formation of Quaternary thrust faults in the San Francisco Bay area. Review of published geologic field data and interpretation of seismic reflection profiles have led Crouch and others (1984) to suggest that many of the faults west of the San Andreas fault and offshore central California are post-Miocene thrust faults. Crouch and others' (1984) interpretations are controversial because most discussion to date emphasizes strike-slip faults in the offshore (Silver and Normark, 1978). In addition to these geologic observations and interpretations, there have been numerous earthquakes throughout the central Coast Ranges that have pure dip-slip thrust or reverse-fault focal mechanisms (Eaton, 1985b). These observations and interpretations suggest that compression on thrust faults is an integral part of the active deformation of the central Coast Ranges.

Two recently proposed plate-tectonic models provide possible explanations for the onset of late Cenozoic compression of the central California Coast Ranges. Cox and Engebretson (1985), using Pacific plate hot-spot tracks, suggested that the compressive strains are related to a change in Pacific/North American plate motions that increased the convergent component across the transform plate boundary to ~5 mm/yr at about 5 Ma. A similar analysis by F. Pollitz (unpub. data) suggests compression of 8 mm/yr. Analyzing the Quaternary velocity field of subregional plate movements in the western United States, Minster and Jordan (1984) also concluded that compression should be occurring across the central California Pacific/North American plate boundary at a rate of 4–13 mm/yr.

Although the onset of Quaternary compression can be related to plate motions, the structural geometry and deformation mechanisms across this plate boundary remain problematic. Any viable structural model across the Pacific and North American plate boundary will have to accommodate concurrent thrust faulting and strike-slip faulting in the shallow crust and relate these features to convergent strike-slip motion between the plates. We offer one possible structural interpretation that can accommodate the major geologic relationships across the central Coast Ranges.

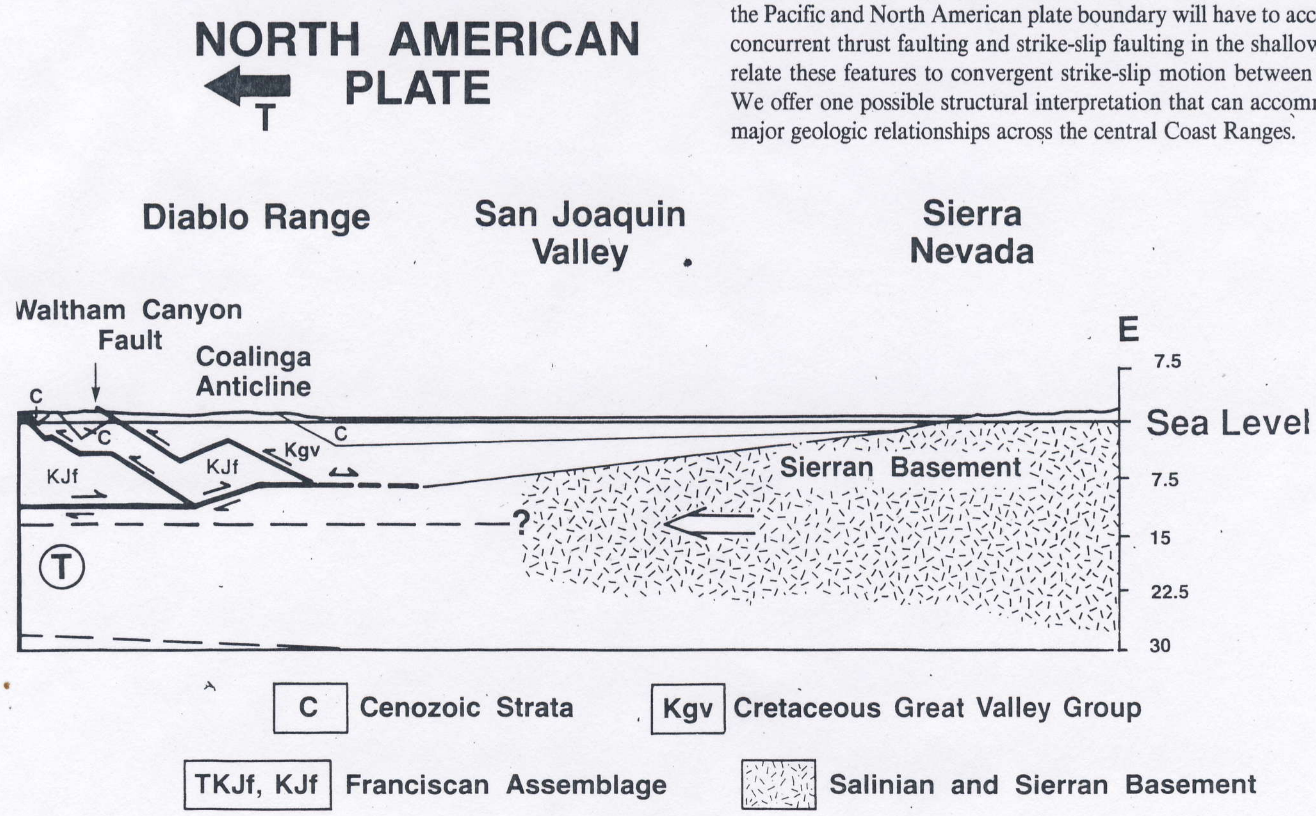


Figure 12. (*Continued*).

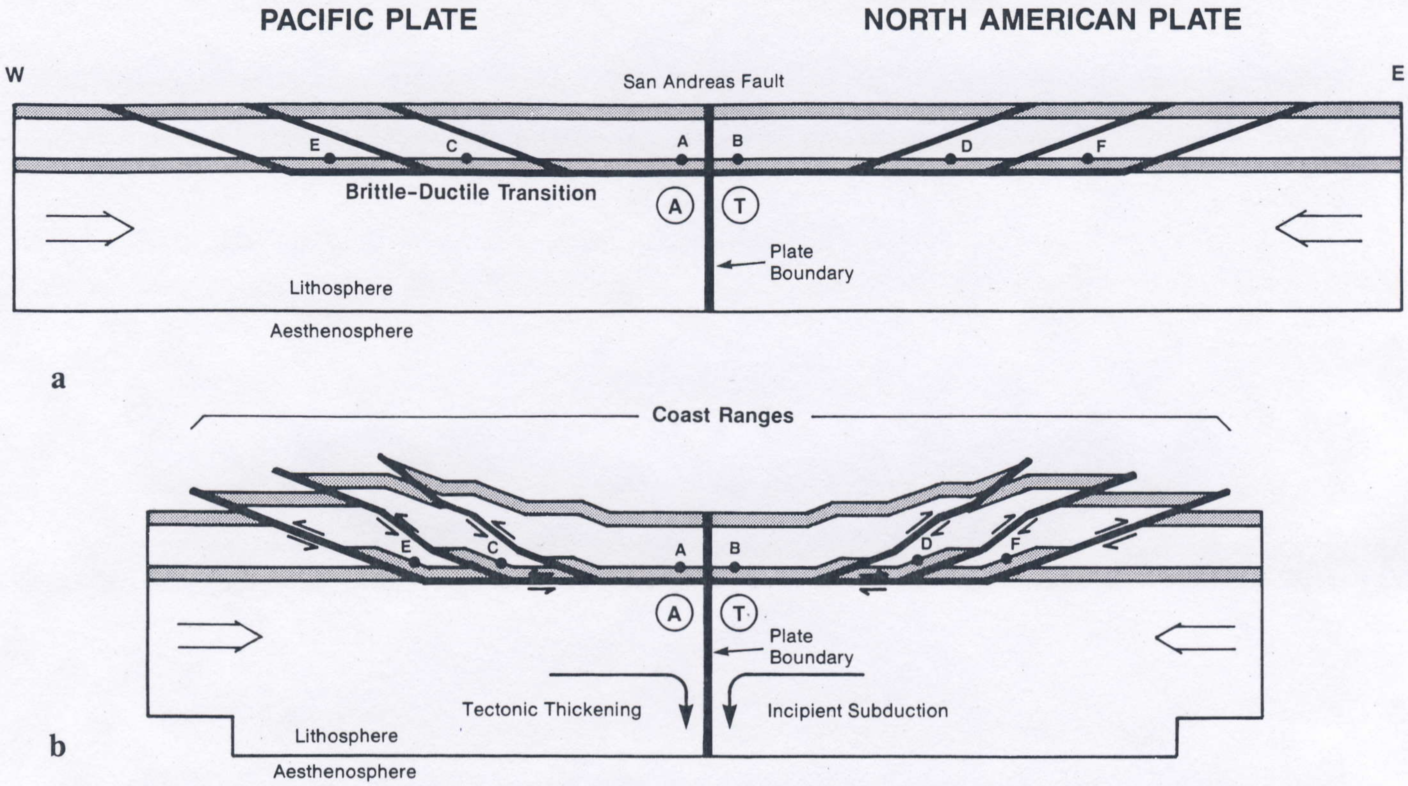


Figure 13. Kinematic model showing the interaction between concurrent thrust faults and strike-slip faults across the North American/Pacific plate boundary in central California. a. The initial positions of thrust ramps and material points A, B, C, D, E, and F and the San Andreas fault zone are shown prior to compression. The thrusts root in the brittle-ductile transition zone. b. After a shortening of 20%, there is topographic uplift of the Coast Ranges along the thrusts, with points C, D, E, and F moving closer to the San Andreas fault zone whereas points A and B remain a fixed distance from the San Andreas fault. The lower crust and lithosphere below the brittle-ductile transition zone must also be shortened by ductile tectonic thickening or incipient subduction.

Our structural interpretation can be extended across the plate boundary from the Sierra Nevada, the San Joaquin Valley, the Diablo Range, the Gabilan Range, and the Santa Lucia Range to the offshore (Fig. 12). The strike-slip motion across the plate boundary is largely confined to the San Andreas fault zone and possible faults offshore. Compressive folding and faulting in the Coast Ranges take place largely on thrust faults that root in a basal décollement near the brittle-ductile transition zone. The depth of the brittle-ductile transition zone is inferred to be approximately equivalent to the maximum depth of observed seismicity (12–15 km; Wesson and others, 1977; Eaton, 1985b).

The interpretation from the San Joaquin Valley to the San Andreas fault suggests that the basal décollement is about 12.5 km deep and that thrusts step up from this level to cause the observed folding, faulting, and seismicity (Fig. 6). The total late Cenozoic shortening for the section east of the San Andreas fault is about 11 km. West of the San Andreas fault, we suggest that the recent uplift of the Gabilan Range and Santa Lucia Range is associated with westerly directed thrust faults that root into the same basal décollement (Davis and McIntosh, 1987). The cumulative shortening in our cross section west of the San Andreas fault (Fig. 12) is ~22 km, which was computed by deriving a solution that satisfies the observed structural relief of the individual ranges. The total late Cenozoic shortening in this cross section across the entire Coast Ranges above the brittle-ductile transition is 33 km.

This structural interpretation (Fig. 12) proposes that strain associated with the convergent strike-slip motion between the North American and Pacific plates is resolved into tangential and normal components with respect to the plate boundary. In the shallow crust (above the brittle-ductile transition zone), the tangential strain component is primarily strike-slip motion along the San Andreas fault, whereas the normal strain component is manifested as thrust faults and folds in the Coast Ranges that strike generally parallel to the San Andreas fault and root in the brittle-ductile transition zone.

The proposed kinematics are illustrated in Figure 13, which shows thrust faults in the shallow crust that root in a detachment at the brittle-ductile transition zone. As convergence occurs, points A and B can remain a constant distance from the San Andreas fault, whereas points C, D, E, and F move toward the plate boundary with plate convergence, motion on the thrusts, and over-all lithospheric shortening. The fold belt propagates westward into the offshore west of the San Andreas fault and eastward into the San Joaquin Valley east of the San Andreas fault even though net motion of material points within the fold belt is toward the San Andreas fault (plate boundary). The lower crust and lithosphere are shortened an amount equivalent to that in the shallow crust by either tectonic thickening or incipient subduction into the asthenosphere. The estimated 33 km of late Cenozoic shortening in the structural interpretation through the shallow crust (Fig. 12) must be matched by a similar amount of shortening below the detachment down to the base of the lithosphere, as shown in Figure 13b.

The crustal structure near our regional interpretation in the central California Coast Ranges (Fig. 12), on the basis of Pn traveltimes of re-

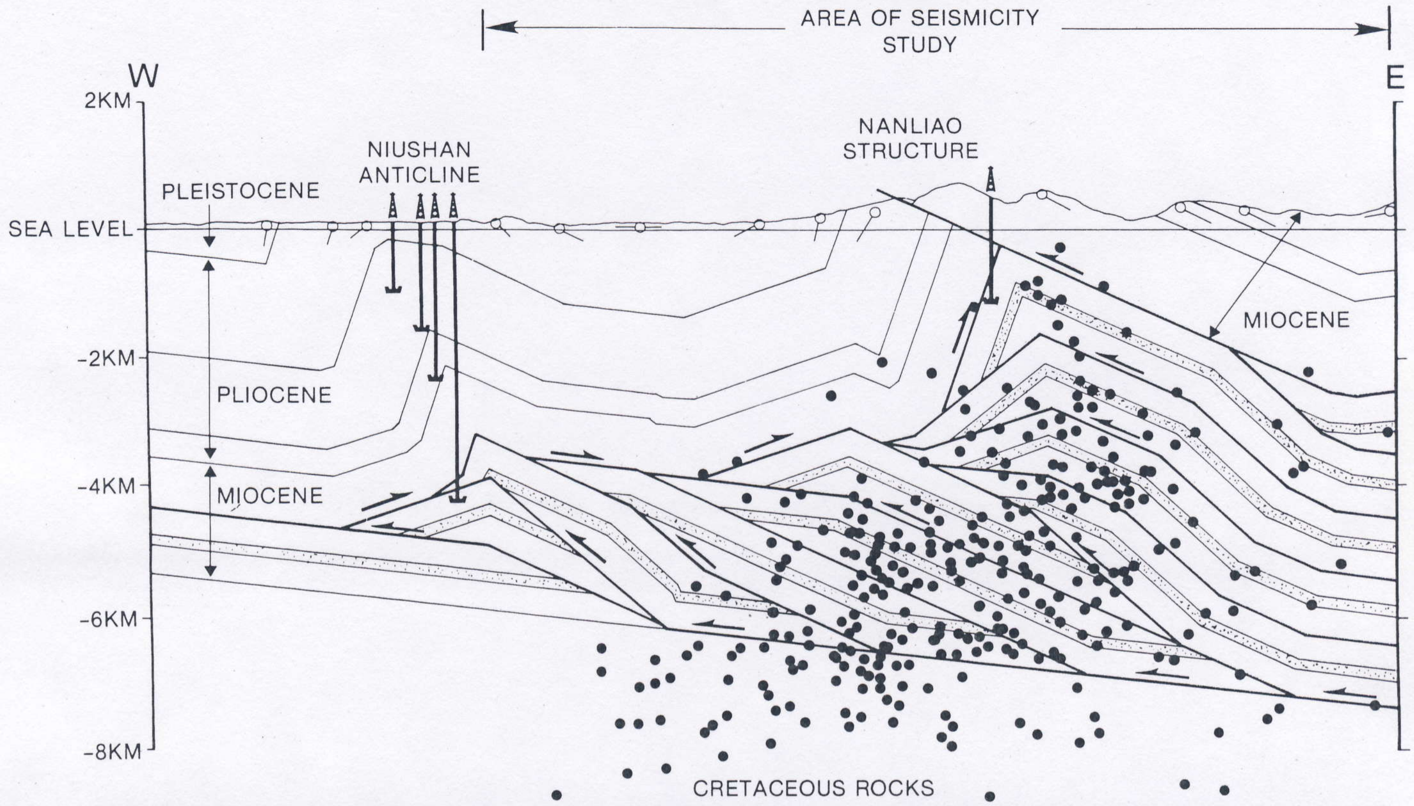


Figure 14. Interpretation of the Nanliao area, Taiwan, showing the relation of the thrust faults in the imbricate wedge to earthquake hypocenters (after Suppe, 1980). Most of the seismicity is associated with blind thrusts, and only one thrust reaches the surface.

gional earthquakes (Oppenheimer and Eaton, 1984), shows the Moho to dip eastward from about 22 km depth near the coast to about 30 km depth along the west side of the San Joaquin Valley. The observed eastward crustal thickening may be related to convergence across the plate boundary. We have been unable to locate studies that attempt to determine the structure of the lithosphere-asthenosphere boundary in central California.

The western Transverse Ranges provide a possible analogue to our model of the central Coast Ranges. The late Cenozoic crustal structure of the western Transverse Ranges is dominated by thrust faulting and major detachments (Yeats, 1981, 1983; Davis, 1986; Namson, 1987). A thick lithospheric anomaly is observed beneath the Transverse Ranges in southern California (Raikes, 1980; Hearn, 1984; Humphreys and others, 1984; Sheffels and McNutt, 1986) and is believed to be the result of plate convergence and incipient subduction (Bird and Rosenstock, 1984). The shallow crustal shortening and lithospheric anomaly suggest a decoupling within the lithosphere and an attempt at balancing lithospheric shortening.

Using a two-dimensional analysis to determine the shortening through the lithosphere in Figure 12 yields an incomplete answer because the blocks on either side of the San Andreas fault are moving past one another. An exact answer could be determined if both shortening and strike-slip offsets across the plate boundary were restored through geologic time. The structural relief and topographic relief are relatively constant throughout the central Coast Ranges along both sides of the San Andreas fault, however, which suggests that deformation is relatively constant across the central Coast Ranges and not inconsistent with our model.

Recent studies of the current stress field in central California using bore-hole break-out data show the principal compressive stress to be oriented normal to the San Andreas fault (V. Mount and J. Suppe, unpub. data). These findings support our model of resolving the strain across the plate boundary into components normal and tangential to the San Andreas fault and suggest that the orientation of the Quaternary principal strain axes, determined from map-scale folds and faults, is roughly coincident with the present orientation of the principal stress axes.

IMPLICATIONS OF THRUST-RELATED FOLDING FOR EARTHQUAKE RISK STUDIES

If the thrust-belt model for the Coalinga-Avenal area is valid, and it is reasonable to extend the model to explain the late Cenozoic deformation along the west and south margins of the San Joaquin Valley and the Coast Ranges, then there are important implications for the future of earthquake risk studies in these areas. Surface deformation associated with the May 2, 1983, Coalinga earthquake has been studied intensely in the months following the main shock (King and Stein, 1983; Stein, 1983; Hart and McJunkin, 1983; Rymer and others, 1983). These studies include mapping the areas of minor surface rupture and landslides, as well as detailed analysis of elevation changes in the Coalinga area. These types of surface deformation analyses and trenching of active faults are the basis for present geological earthquake hazard studies in California and many parts of the world.

The approach of using surface deformation analyses to evaluate earthquake hazards is based on well-documented studies of strike-slip faults such as the San Andreas fault (Allen, 1975, 1981; Sieh, 1978) and other large strike-slip faults (Clark, 1972; Allen, 1975, 1981). There are assumptions in this approach that are based on geologic observations along these strike-slip faults. (1) The late Quaternary surface deformation along strike-slip faults provides a first-order approximation of active fault movement at depth during a moderate to great earthquake. (2) The surface

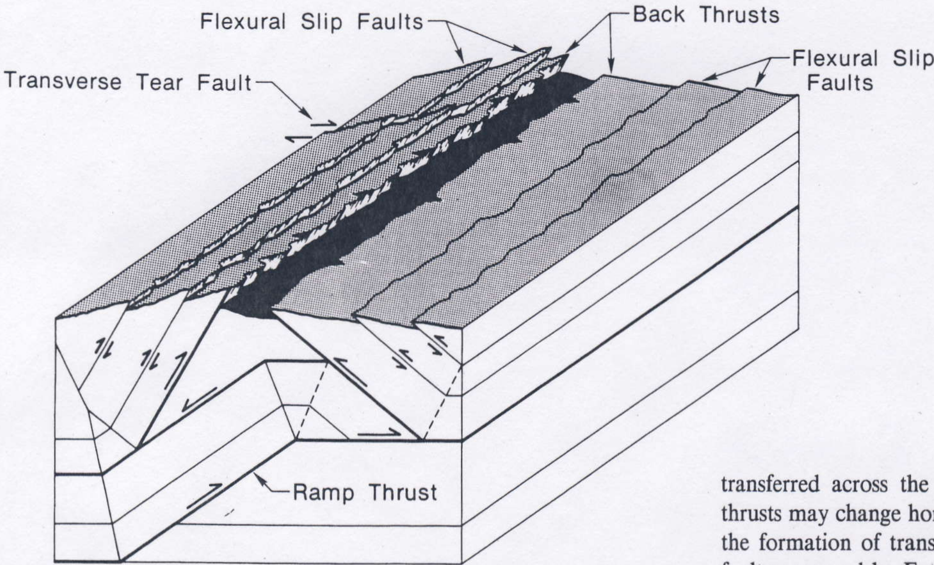


Figure 15. Hypothetical surface deformation associated with ramp-related folds like the Coalinga anticline. These hypothetical surface ruptures are indirectly related to the main fault, illustrating possible complexities of relating surface deformation and associated earthquakes at depth. The deformation mechanisms may explain surface deformation associated with the Coalinga earthquake sequence (after Namson and others, in press).

deformation associated with earthquakes on large strike-slip faults is confined to narrow zones less than tens of metres wide, and displacements recur within this zone over periods of at least several thousand years (Sieh, 1978; Allen, 1981). (3) The narrow fault zone is assumed to be nearly vertical for at least the upper several kilometres of the crust. The observations supporting these assumptions indicate a relatively simple mechanical system in which deformation during an earthquake is transferred from depth to the surface along a narrow vertical strike-slip fault. In active fold and thrust belts, however, the interaction between fault movement at depth and surface deformation is more complex and does not allow for a simple relationship between surface observation and the fault geometry and slip at depth.

Active fold and thrust belts are subject to two major problems that prevent an obvoius one-to-one relationship between surface deformation and fault behavior at depth. First, there is the possibility of blind thrusting, wherein fault slip does not reach the surface and the shortening is consumed in developing folds. As poignantly shown at Coalinga and Avenal, at least moderate-sized earthquakes can take place at depth without accompanying surface rupture. In addition, the geometry of thrust systems can be very complex, involving imbricates, duplexes, and back thrusts (Dahlstrom, 1970; Jones, 1982; Boyer and Elliott, 1982). Some of these complexities are illustrated by Suppe's (1980) interpretation of the Nanliao structure from the active fold and thrust belt of western Taiwan (Fig. 14). The folds in this area are associated with an intricate array of blind imbricate thrust faults that are seismically active. The hypocenters of earthquakes ($2 < M < 4$; Wu and others, 1979) occurring between February 1973 and July 1975 show a good correlation with the position of the imbricated wedge in the structural solution. Only one thrust fault is observed at the surface even though there is intense structural deformation and abundant seismicity.

Second, there is a complex relationship between deformation that does reach the surface and fault movement at depth. To emphasize this problem, a block model of a fault-bend fold forming just below the surface is presented (Fig. 15). This model is similar to our interpretation of the Coalinga and North Dome anticlines. The model presents a hypothetical situation that illustrates a variety of surface deformation that can result from movement on a thrust fault at depth. Flexural-slip faults shown as shear couples form in parallel folding, and the magnitude of slip is directly related to the dip angle and thickness of the slip packages (Ramsay, 1974). Flexural-slip faults are commonly found in fold belts around the world (Yeats, 1986). Back thrusts may also form as slip with reverse vergence is transferred across the structure along the décollement horizon. These thrusts may change horizons along the strike of the structure, resulting in the formation of transverse tear faults. Perhaps some of the subsidiary faults proposed by Eaton (1985a) for aftershocks of the Coalinga earthquake could be the result of structures similar to those shown in Figure 15.

CONCLUSIONS

The structural analysis and geologic history of folds along the west and south margins of the San Joaquin Valley, derived from a variety of surface and subsurface data, suggest that the folds are part of an actively developing fold and thrust belt rather than part of the wrench tectonics generally cited (Harding, 1976). In the thrust-belt interpretation, the Coalinga and Avenal earthquakes resulted from movement on a blind thrust(s). Movement on this thrust(s) during late Pliocene and Quaternary time has produced the Coalinga and North Dome anticlines, which are interpreted to be fault-bend folds. Other folds in the deformed belt that can be related to thrust faults occur at Wheeler Ridge, in the San Emigdio Mountains, and at Kettleman South Dome. These folds are geometrically similar to fault-bend or fault-propagation folds.

Other studies in the Coast Ranges (on both sides of the San Andreas fault) have cited additional evidence for late Cenozoic compressive deformation and thrust faulting throughout this region (Page and Engebretson, 1984; Crouch and others, 1984). Plate motion studies support development of a compressive component across the Pacific/North American plate boundary in central California during late Cenozoic time. We propose a model in which the strain associated with the transpressive plate motions is resolved into a tangential component of strike slip along the San Andreas fault and a normal component of compression along thrust faults and folds that strike nearly parallel to the San Andreas fault. In a cross section across the plate boundary, we suggest that the thrust faults root in a décollement at the brittle-ductile transition zone and that shortening above this décollement occurs in folds and splay thrusts. Below the décollement, shortening in the lower crust and lithosphere is accommodated by ductile processes of tectonic thickening of the lithospheric plates.

If much of the seismicity along the south and west sides of the San Joaquin Valley is due to a developing fold and thrust belt, then previous surface studies for seismic risk evaluation may have to be reconsidered in areas of folding and thrust faulting. Fold and thrust belts are characterized by two features that complicate surface evaluations of seismic potential. First, in fold and thrust belts, many faults do not reach the surface (blind thrusts), yet these faults can have considerable offset at depth. Second, surface rupture or tilting may occur that is not simply related to fault movement at depth. Construction of balanced cross sections through folds and fold belts will be necessary in order to determine the subsurface geometry and seismic potential of active thrust faults.

ACKNOWLEDGMENTS

We would like to thank ARCO Oil and Gas Company for permission to release this manuscript. Numerous reviews improved the manuscript, and we would like to thank W. J. Bazeley, G. Cushing, S. Graham, T. Hudson, J. Ligon, K. Meisling, D. Nedland, V. Sare, G. Viele, M. Wood, and R. Yeats.

REFERENCES CITED

Addicott, W. O., 1972, Biostratigraphy and correlation of Tertiary sandstones at Big Tar Canyon, Reef Ridge, California, *in* Geology and oil fields, west side central San Joaquin Valley: American Association of Petroleum Geologists, Pacific Section, Guidebook, p. 65–69.

Adegoke, O. S., 1969, Stratigraphy and paleontology of the marine Neogene Formations of the Coalinga region, California: University of California Publications in Geological Sciences, v. 80, 241 p.

Allen, C. R., 1975, Geological criteria for evaluating seismicity: Geological Society of America Bulletin, v. 86, p. 1041–1067.

——— 1981, The modern San Andreas fault, *in* Ernst, G. W., ed., The geotectonic development of California: Englewood Cliffs, New Jersey, Prentice-Hall, p. 311–334.

Bandy, O. L., and Arnal, R. E., 1969, Middle Tertiary basin development, San Joaquin Valley, California: Geological Society of America Bulletin, v. 80, p. 783–820.

Bate, M. A., 1984, Temblor and Big Blue Formations: Interpretation of depositional environment sequence on Coalinga anticline, Fresno County, California [M.S. thesis]: Stanford, California, Stanford University, 123 p.

Bird, P., and Rosenstock, R.W., 1984, Kinematics of present crust and mantle flow in southern California: Geological Society of America Bulletin, v. 95, p. 946–957.

Boyer, S. E., and Elliott, D., 1982, Thrust systems: American Association of Petroleum Geologists, v. 66, p. 1196–1230.

Carls, J. M., 1951, Recent developments in Wheeler Ridge oil field: California Division of Oil and Gas Summary of Operations of California Oil Fields, v. 37.

——— 1955, Wheeler Ridge oil field Eocene development: California Division of Oil and Gas Summary of Operations, v. 41, n. 1, p. 41–48.

Christensen, M. N., 1965, Late Cenozoic deformation in the Coast Ranges of California: Geological Society of America Bulletin, v. 76, p. 1105–1124.

Clark, M. M., 1972, Surface rupture along the Coyote Creek fault: U.S. Geological Survey Professional Paper 450B, p. B15–B19.

Clark, M., Harms, K., Lienkaemper, J., Perkins, J., Rymer, M., and Sharp, R., 1983, The search for surface faulting, *in* The Coalinga earthquake sequence commencing May 2, 1983: U.S. Geological Survey Open-File Report 83-511, p. 8–11.

COSUNA, 1984, Correlation of stratigraphic units of North America project, central California region: Tulsa, Oklahoma, American Association of Petroleum Geologists.

Cox, A., and Engebretson, D. C., 1985, Change in motion of Pacific plate at 5 m.y. B.P.: Nature, v. 313, p. 472–474.

Crouch, J. K., Bachman, S. B., and Shay, J. T., 1984, Post-Miocene compressional tectonics along the central California margin, *in* Crouch, J. K., and Bachman, S. B., eds., Tectonics and sedimentation along the California margin: Pacific Section of Society of Economic Paleontologists and Mineralogists, v. 38, p. 37–54.

Crowell, J. C., 1979, The San Andreas fault system through time: Geological Society of London Journal, v. 136, p. 293–302.

Dahlstrom, C.D.A., 1970, Structural geology in the eastern margin of the Canadian Rocky Mountains: Bulletin of Canadian Petroleum Geology, v. 18, p. 332–406.

Davis, T. L., 1983, Late Cenozoic structure and tectonic history of the western "big bend" of the San Andreas fault and adjacent San Emigdio Mountains [Ph.D. thesis]: Santa Barbara, California, University of California at Santa Barbara, 579 p.

——— 1986, A structural outline of the San Emigdio Mountains, *in* Davis, T. L., and Namson, J., eds., Geologic transect across the western Transverse Ranges: Society of Economic Paleontologists and Mineralogists, Pacific Section, Guidebook, p. 23–32.

Davis, T. L., and Lagoe, M. B., 1984, Cenozoic structural development of the north-central Transverse Ranges and southern margin of the San Joaquin Valley: Geological Society of America Abstracts with Programs, v. 16, p. 484.

Davis, T. L., and McIntosh, K. D., 1987, A retrodeformable structural solution across the southern Coast Ranges and implications for seismically active structures: Geological Society of America Abstracts with Programs, v. 19, p. 370.

Dibblee, T. W., Jr., 1971, Geologic maps of the Coalinga, Joaquin Rocks, New Idria and Priest Valley 15′ quadrangles: U.S. Geological Survey Open-File Map 71-87, Sheets 5, 8, 10, and 15, scale 1:62,500.

——— 1973, Regional geologic map of San Andreas and related faults in Carrizo Plain, Temblor, Caliente and La Panza Ranges and vicinity, California: U.S. Geological Survey Map I-757, scale 1:100,000.

——— 1974, Geologic map of the San Emigdio quadrangle, California: U.S. Geological Survey Open-File Map, scale 1:62,500.

Division of Oil and Gas, 1982, California oil and gas fields, central California: California Division of Oil and Gas, TR11-R.

Eaton, J. P., 1985a, The May 2, 1983, Coalinga earthquake and its aftershocks: A detailed study of the hypocenter distribution and of the focal mechanisms of the larger aftershocks: U.S. Geological Survey Open-File Report 85-44, p. 132–201.

——— 1985b, Regional seismic background of the May 2, 1983, Coalinga earthquake: U.S. Geological Survey Open-File Report 85-44, p. 44–60.

Eaton, J., Cockerham, R., and Lester, F., 1983, Study of the May 2, 1983, Coalinga earthquake and its aftershocks, based on the USGS seismic network on northern California, *in* Bennett, J. H., and Sherburne, R. W., eds., The 1983 Coalinga, California, earthquake: California Division of Mines and Geology Special Publication 66, p. 261–273.

Fielding, E., Barazangi, M., Brown, L., Oliver, J., and Kaufman, S., 1984, COCORP seismic profiles near Coalinga, California: Subsurface structure of the western Great Valley: Geology, v. 12, p. 268–273.

Foss, C. D., 1972, A preliminary sketch of the San Joaquin Valley stratigraphic framework, *in* Rennie, E. W., Jr., Geology and oil fields, west side central San Joaquin Valley: American Association of Petroleum Geologists, Pacific Section, Guidebook, p. 40–49.

Foss, C. D., and Blaisdell, R., 1968, Stratigraphy of the west side southern San Joaquin Valley, *in* Geology and oil fields, west side southern San Joaquin Valley: American Association of Petroleum Geologists, Pacific Section, Guidebook, p. 33–42.

Fuller, D. R., and Real, C. R., 1983, High-angle reverse faulting, a model for the 2 May 1983 Coalinga earthquake, *in* Bennett, J. H., and Sherburne, R. W., eds., The 1983 Coalinga, California, earthquake: California Division of Mines and Geology Special Publication 66, p. 177–184.

Harding, T. P., 1976, Tectonic significance and hydrocarbon trapping consequences of sequential folding synchronous with San Andreas faulting, San Joaquin Valley, California: American Association of Petroleum Geologists Bulletin, v. 60, p. 356–378.

Hart, E. W., and McJunkin, R. D., 1983, Surface faulting northwest of Coalinga, California, June and July 1983, *in* Bennett, J. H., and Sherburne, R. W., eds., The 1983 Coalinga, California, Earthquake: California Division of Mines and Geology Special Publication 66, p. 201–220.

Hearn, T. M., 1984, Pn travel times in southern California: Journal of Geophysical Research, v. 89, p. 1843–1855.

Hill, M. L., 1984, Earthquakes and folding, Coalinga, California: Geology, v. 12, p. 711–712.

Hoots, H. W., 1930, Geology and oil resources along the southern border of the San Joaquin Valley, California: U.S. Geological Survey Bulletin 812-D, p. 243–332.

Hopson, C. A., Mattinson, J. M., and Pessagno, E. A., Jr., 1981, Coast Range Ophiolite, western California, *in* Ernst, W. G., ed., The geotectonic development of California: Englewood Cliffs, New Jersey, Prentice-Hall, p. 418–510.

Humphreys, E., Clayton, R. W., and Hager, B. H., 1984, A tomographic image of mantle structure beneath southern California: Geophysical Research Letters, v. 11, p. 625–627.

Jennings, C. W., and Strand, R. G., 1958, Geologic map of California, Santa Cruz sheet: California Division of Mines and Geology, scale 1:250,000.

Jones, P. B., 1982, Oil and gas beneath east-dipping underthrust faults in the Alberta foothills, *in* Powers, R. B., eds., Geologic studies of the Cordilleran thrust belt: Rocky Mountain Association of Geologists, v. 1, p. 61–74.

Kaplow, E. J., 1945, Coalinga oil field, *in* Summary of operations, California oil fields: California Department of Natural Resources, Division of Oil and Gas, v. 31, p. 5–22.

King, G., and Stein, R., 1983, Surface folding, river terrace deformation rate and earthquake repeat time in a reverse faulting environment: The Coalinga, California, earthquake of May 1983, *in* Bennett, J. H., and Sherburne, R. W., eds., The 1983 Coalinga, California, earthquake: California Division of Mines and Geology Special Publication 66, p. 165–176.

Lowell, J. C., 1972, Spitsbergen Tertiary orogenic belt and the Spitsbergen fracture zone: Geological Society of America Bulletin, v. 83, p. 3091–3102.

Mallory, V. S., 1959, Lower Tertiary biostratigraphy of the California Coast Ranges: Tulsa, Oklahoma, American Association of Petroleum Geologists, 416 p.

Medwedeff, D. A., 1984, Structural analysis of fault-propagation folding at Wheeler Ridge and the adjacent White Wolf fault, San Joaquin basin, California: a report to the Department of Geological and Geophysical Sciences, Princeton University, 15 p.

Minster, J. B., and Jordan, J. H., 1984, Vector constraints on Quaternary deformation of the western United States east and west of the San Andreas fault, *in* Crouch, J. K., and Bachman, S. B., eds., Tectonics and sedimentation along the California margin: Pacific Section of the Society of Economic Paleontologists and Mineralogists, v. 38, p. 1–16.

——— 1987, Structural transect through the Ventura basin and western Transverse Ranges, *in* Davis, T. L., and Namson, J. S., eds., Structural evolution of the western Transverse Ranges: Society of Economic Paleontologists and Mineralogists, Pacific Section, Guidebook.

Namson, J. S., and Davis, T. L., 1984, Deformational history, thrust-belt structural styles and plate tectonic origin of Coast Range structures along the San Joaquin Valley, California: Geological Society of America Abstracts with Programs, v. 16, p. 607.

Namson, J. S., Davis, T. L., and Lagoe, M. B., 1983, Thrust-fold deformation style of seismically active structures near Coalinga, California [abs.]: EOS (American Geophysical Union Transactions), v. 64, no. 5, p. 749–750.

——— 1987, Tectonic history and thrust-fold deformation style of seismically active structures near Coalinga, California: U.S. Geological Survey Professional Paper (in press).

Nilsen, T. H., and McKee, E. H., 1979, Paleogene paleogeography of the western United States, *in* Cenozoic paleogeography of the western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Symposium, 3rd, p. 257–276.

Nilsen, T. H., Dibblee, T. W., and Addicott, W. O., 1973, Lower and middle Tertiary stratigraphic units of the San Emigdio and western Tehachapi Mountains: U.S. Geological Survey Bulletin 1372-H, p. H1–H23.

Oakeshott, G. B., 1968, Diapiric structures in Diablo Range, California, *in* Braunstein, Jules, and O'Brien, G. D., eds., Diapirism and diapirs, a symposium: American Association of Petroleum Geologists Memoir 8, p. 228–243.

O'Connel, D. R., and Murtha, P. E., 1983, Source parameters of Coalinga aftershocks from the U.C. Berkeley portable digital array, *in* Bennett, J. H., and Sherburne, R. W., eds., The 1983 Coalinga, California, earthquake: California Division of Mines and Geology Special Publication 66, p. 293–306.

Oppenheimer, D. H., and Eaton, J. P., 1984, Moho orientation beneath central California from regional earthquake travel times: Journal of Geophysical Research, v. 89, p. 10267–10282.

Page, B. M., 1981, The southern Coast Ranges, *in* Ernst, W. G., ed., The geotectonic development of California: Englewood Cliffs, New Jersey, Prentice-Hall, p. 329–417.

——— 1985, Geologic background of the Coalinga earthquake of May 2, 1983: U.S. Geological Survey Open-File Report 85-44, p. 4–9.

Page, B. M., and Engebretson, D., 1984, Correlation between the geologic record and computed plate motions for central California: Tectonics, v. 3, p. 133–156.

Payne, M., 1962, Type Panoche Group and overlying Moreno and Tertiary strata on the west side of the San Joaquin Valley: California Division of Mines and Geology Bulletin 181, p. 165–175.

Raikes, S. A., 1980, Regional variations in upper mantle structure beneath southern California: Royal Astronomical Society Geophysical Journal, v. 63, p. 187–216.

Ramsay, J. G., 1974, Development of chevron folds: Geological Society of America Bulletin, v. 85, p. 1741–1754.

Repenning, C. A., 1976, *Enhydra* and *Enhydriodon* from the Pacific coast of North America: U.S. Geological Survey Research Journal, v. 4, p. 305–315.

Rymer, M. J., Harms, K. K., Clark, M. M., and Lienkaemper, J. J., 1983, Surface faulting associated with an aftershock of the May 2, 1983, Coalinga, California, earthquake [abs.]: EOS (American Geophysical Union Transactions), v. 64, p. 748.

Sheffels, B., and McNutt, M., 1986, Role of subsurface loads and regional compensation in the isostatic balance of the Transverse Ranges, California: Evidence for intracontinental subduction: Journal of Geophysical Research, v. 91, p. 6419–6431.

Sieh, K. E., 1978, Slip along the San Andreas fault associated with the great 1857 earthquake: Seismological Society of America Bulletin, v. 68, p. 1421–1448.

Silver, E. A., and Normark, W. R., 1978, San Gregorio–Hosgri fault zone: California Division of Mines and Geology Special Report 137, 56 p.

Stein, R. S., 1983, Reverse slip on a buried fault during the 2 May 1983 Coalinga earthquake: Evidence from geodetic elevation changes, *in* Bennett, J. H., and Sherburne, R. W., eds., The 1983 Coalinga, California, earthquake: California Division of Mines and Geology Special Publication 66, p. 151–163.

Suppe, J., 1980, Imbricated structure of western foothills belt, southcentral Taiwan: Petroleum Geology Taiwan, no. 17, p. 1–16.

——— 1983, Geometry and kinematics of fault-bend folding: American Journal of Science, v. 283, p. 684–721.

Suppe, J., and Medwedeff, D. A., 1984, Fault-propagation folding: Geological Society of America Abstracts with Programs, v. 16, p. 67.

Suppe, J., and Namson, J. S., 1979, Fault bend origin of frontal folds of the western Taiwan fold and thrust belt: Petroleum Geology Taiwan, no. 16, p. 1–18.

Sylvester, A. G., and Smith, R. R., 1976, Tectonic transpression and basement-controlled deformation in San Andreas fault zone, Salton Trough, California: American Association of Petroleum Geologists Bulletin, v. 30, p. 2081–2102.

Wentworth, C. M., Walter, A. W., Bartow, J. A., and Zoback, M. D., 1983, Evidence on the tectonic setting of the 1983 Coalinga earthquakes from deep reflection and refraction profiles across the southeastern end of Kettleman Hills in the 1983 Coalinga, California, earthquake, *in* Bennett, J. H., and Sherburne, R. W., eds., The 1983 Coalinga, California, earthquake: California Division of Mines and Geology Special Publication 66, p. 293–306.

Wesson, R. L., Robinson, R., Bufe, C. G., Ellsworth, J. H., Pfluke, J. H., Steppe, J. A., and Seekins, L. C., 1977, Search for seismic forerunners to earthquakes in central California: Tectonophysics, v. 42, p. 111–126.

Wilcox, R. E., Harding, T. P., and Seely, D. R., 1973, Basic wrench tectonics: American Association of Petroleum Geologists Bulletin, v. 57, p. 74–96.

Woodring, W. P., Stewart, R. B., and Richards, R. W., 1940, Geology of the Kettleman Hills oilfield, California: U.S. Geological Survey Professional Paper 195, 170 p.

Wu, F. T., Yeh, Y. H., and Tsai, Y. B., 1979, Seismicity in the Tsengwen reservoir area, Taiwan: Seismological Society of America Bulletin, v. 69, p. 1783–1796.

Yeats, R. S., 1981, Quaternary flake tectonics of the California Transverse Ranges: Geology, v. 9, p. 16–20.

——— 1983, Large scale Quaternary detachments in Ventura basin, southern California: Journal of Geophysical Research, v. 88, p. 569–583.

——— 1986, Active faults related to folding, *in* Active tectonics: Washington, D.C., National Academy Press, p. 63–79.

Manuscript Received by the Society July 16, 1986
Revised Manuscript Received June 8, 1987
Manuscript Accepted July 31, 1987

Proterozoic and Phanerozoic basement terranes of Mexico from Nd isotopic studies

JOAQUIN RUIZ
P. JONATHAN PATCHETT } *Department of Geosciences, University of Arizona, Tucson, Arizona 85721*
FERNANDO ORTEGA-GUTIERREZ *Instituto de Geologia, Universidad Nacional Autonoma de Mexico, Mexico, D.F.*

ABSTRACT

Nd isotopic data were collected on Precambrian crystalline rocks exposed in northern, eastern, and southern Mexico, as well as from lower crustal xenoliths from central Mexico, in order to constrain the age and character of the Mexican basement. The data indicate that basement belonging to the Grenville (1.0 Ga) tectonothermal event extends from Los Filtros, in Chihuahua, northern Mexico, to Oaxaca, in southern Mexico. These rocks all have average Nd crustal residence times (T_{DM} ages) in the range 1.60 to 1.35 Ga. We infer that this results from mixing average 1.9 Ga or older recycled continental crust with 70% to 90% newly derived mantle-crustal material during the Grenville orogeny. To the west of the Precambrian, the basement contains large amounts of Phanerozoic (probably Paleozoic) crust, identified from lower crustal xenoliths with T_{DM} ages less than 1.0 Ga. The crust represented by these xenoliths may have been emplaced as suspect terranes in Mesozoic Cordilleran events. Alternatively, the apparent Paleozoic crust that underlies parts of central Mexico may connect to the Paleozoic metamorphic Acatlan complex in southern Mexico, and together they would constitute a continuation of the Appalachian-Caledonian orogenic belt through Mexico. Our data do not preclude either of these two models.

INTRODUCTION: RELATION OF MEXICO TO NORTH AMERICAN GEOLOGY

The tectonic relationships of Mexico have an inherent complexity not shared by most of the cordillera to the north, because Appalachian, Atlantic Ocean, Gulf of Mexico, and North American Cordilleran features coexist. Fundamental problems have been apparent since the earliest reconstructions of Pangea (Bullard and others, 1965), in which Mexico overlapped with South America. Present paleomagnetic reconstructions (for example, Van der Voo and others, 1976; Anderson and Schmidt, 1983) also show an overlap of South America upon ~50% of Mexico; to accommodate this, Silver and Anderson (1974), de Cserna (1970) and Anderson and Schmidt (1983) suggested great left-lateral displacements that were active during Pangean break-up. Campa and Coney (1983), on the basis of recent tectono-stratigraphic analyses, concluded that about 80% of the country is made up of suspect terranes whose relationship to cratonic North America is uncertain. In these models, much of the Mexican basement must have been elsewhere or did not exist prior to Permo-Triassic times. Unfortunately, there are few pre-Mesozoic and, in particular, Precambrian outcrops in Mexico that allow us to constrain the characteristics of the Mexican basement.

Figure 1 shows the presumed tectonostratigraphic terranes of Mexico. The exact composition of each terrane and its precise boundaries are sometimes difficult to determine because of overlap assemblages that cover two or more terranes. The most conspicuous overlap assemblages are the voluminous middle to late Tertiary volcanic rocks that cover large parts of western (Sierra Madre Occidental) and central Mexico (Trans-Mexican Volcanic Belt), and Cretaceous limestones that cover much of north-central (Mexican Altiplano) and northeastern Mexico (Sierra Madre Oriental). An essential feature of these terranes, if they are really distinct crustal blocks, should be the ages and chemical compositions of their basement rocks.

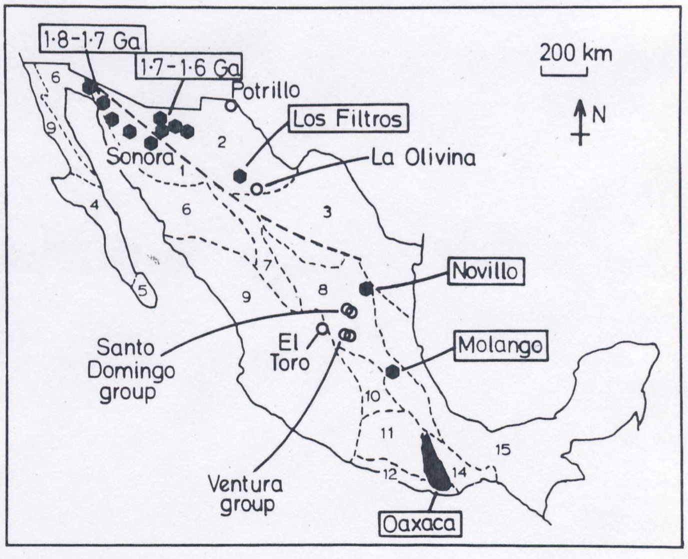


Figure 1. Sampling localities in Mexico. Filled regions and symbols correspond to enclosed names and indicate Precambrian outcrops. The Sonoran Precambrian was studied by Anderson and Silver (1983) and is not included here. Open circles are lower crustal xenolith localities. Thick dashed line is the Mojave-Sonora megashear, as defined by Anderson and Schmidt (1983). Presumed terrane boundaries are from Coney and Campa (1984). Numbers in map correspond to the following terranes: (1) Caborca, (2) Chihuahua (North America), (3) Coahuila, (4) Vizcaino, (5) La Paz, (6) Cortez, (7) Parral, (8) Sierra Madre, (9) Guerrero, (10) Toliman, (11) Acatlan, (12) Xolapa, (13) (darkened terrane) Oaxaca, (14) Zapoteca, (15) Maya.

Geological Society of America Bulletin, v. 100, p. 274–281, 5 figs., 1 table, February 1988.