Kinematic data for the Coast Range fault and implications for exhumation of the Franciscan subduction complex

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ABSTRACT

Kinematic data from two segments of the Coast Range fault are used to test the hypothesis that the Franciscan subduction complex was exhumed by extensional faulting. The data reveal a consistent geometry for the principal directions of brittle strain. The maximum extension direction has an east-west orientation and lies subperpendicular to the present attitude of the Coast Range fault, which dips steeply to the east. The maximum shortening direction is subvertical and lies at a low angle to the present down-dip direction of the fault. Given that the Coast Range fault probably formed with a gentle dip, our results indicate subhorizontal crustal shortening in a northeast direction, which is at variance with interpretations that invoke regional-scale extension between the Franciscan subduction complex and the overlying Coast Range ophiolite and Great Valley Group. We favor a model involving out-of-sequence thrust faults. Such a model is consistent with fault-parallel contraction and the pronounced discontinuity in metamorphic grade across the Coast Range fault, as well as substantial thinning of the Coast Range ophiolite. This interpretation implies that erosion, not extensional faulting, was the major process that exhumed the Franciscan subduction wedge during the Late Cretaceous.

INTRODUCTION

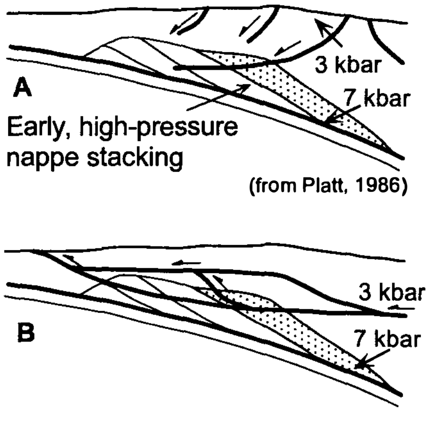
The Franciscan subduction complex of western California is widely regarded as an example of a convergent wedge that underwent a phase of subhorizontal extension (e.g., Platt, 1986). The primary evidence for this interpretation is an attenuated metamorphic section with high-pressure metamorphic rocks of the eastern Franciscan juxtaposed against low-pressure rocks in the overlying structural lid. However, out-of-sequence thrust faults—defined as faults that step back and cut through the rearward or more internal part of a contractional wedge—can also cause attenuation of a section if the section dips more steeply than the faults (Fig. 1). The main distinction between these options is the relative direction of slip on the Coast Range fault. Therefore, we present new kinematic data for two serpentinitic fault zones of the Coast Range fault.

OVERVIEW

The Coast Range fault is an important structure of the Mesozoic-Cenozoic convergent margin of western North America (Fig. 2) (e.g., Cowan and Bruhn, 1992). The fault juxtaposes the Franciscan subduction complex in the footwall against a fore-arc massif in the hanging wall, which comprises the Coast Range ophiolite and the overlying Great Valley fore-arc basin. The fault zone itself is commonly decorated by serpentinite-rich shear zones, presumably derived from ultramafic rocks of the overlying ophiolite. Throughout most of California, the Coast Range fault has been tilted to the east with the formation of the Great Valley homocline, which flanks the east side of the Coast Range uplift.

We focus here on the Eastern belt of the Franciscan complex, which constitutes the footwall of the Coast Range fault. This belt is made up of several thick, gently dipping fault-bounded units, each of which contains a relatively coherent internal stratigraphy (e.g., Worrall, 1981). The two main units are the Yolla Bolly terrane and the structurally higher Pickett Peak terrane (Blake et al., 1988). Metamorphism ranges from lawsonite-albite to blueschist facies; maximum temperatures and pressures are about 150–345 °C and 6 to 9 kbar (Blake et al., 1988; Ernst, 1993), indicating a depth of 22–33 km. Isotopic ages from the Eastern belt indicate a protracted metamorphic history involving Cretaceous high pressure and slow cooling through the early Cenozoic (e.g., Lanphere et al., 1978; Dumitru, 1989). The oldest metamorphic ages (125–152 Ma) come from rocks of the Pickett Peak terrane. Regional metamorphism of the Yolla Bolly terrane probably occurred about 90 Ma. Pronounced differences in metamorphic grade indicate that the faults that currently juxtapose units in the Eastern belt formed mainly after high-pressure metamorphism (e.g., Suppe, 1973).

The hanging wall of the Coast Range fault is the Jurassic Coast Range ophiolite and the Upper Jurassic and Cretaceous Great Valley Group (Ingersoll, 1979). The Coast Range ophiolite shows zeolite to prehnite-pumpellyite facies, indicating pressures < 3.5 kbar



(from Platt, 1986)

Figure 1. Illustration of metamorphic break due to superimposed (A) normal faults or (B) out-of-sequence thrust faults.

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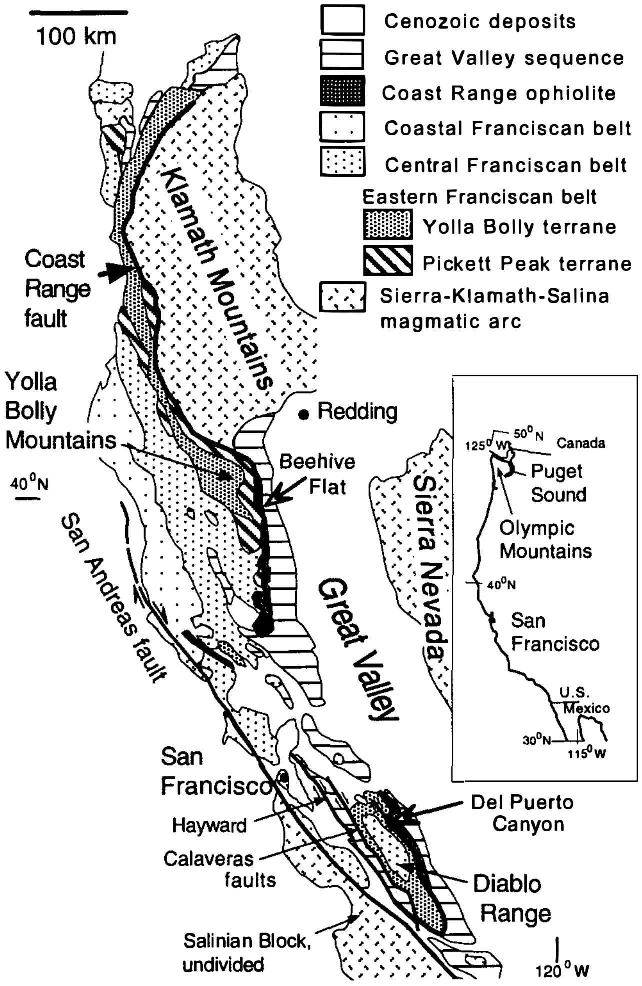

Figure 2. Geologic map showing main Mesozoic tectonic elements of western California and two study areas along Coast Range fault, at Beehive Flat and at Del Puerto Canyon. Note that Diablo Range uplift is flanked by strike-slip faults related to modern San Andreas fault.

and depths < 13 km (e.g., Platt, 1986). Thus, the amount of metamorphic section missing at the Coast Range fault is about 9 to 20 km.

KINEMATIC ANALYSIS

Method

Within large-scale brittle fault zones, it is common to find an array of fault surfaces with widely varying orientations and slip directions. The integrated effect of slip on these surfaces accounts, at least in part, for the overall displacement across the fault zone. The geometry of fibers and fractures on slickensided surfaces can be used to deduce the direction and sense of slip on individual faults (Hancock, 1985). Modern studies of brittle fault zones indicate that slip on individual faults can be integrated to determine the overall brittle strain within the zone (e.g., Marrett and Allmendinger, 1990). Furthermore, these studies show that there is a power-law distribution of fault sizes and slip magnitudes, so that small faults, as judged by their size and slip magnitude, greatly predominate in number over large faults. The slip direction on these small faults can be used to estimate the principal directions of brittle strain for the overall fault zone.

We have used the pressure-tension method to estimate principal directions of brittle strain (Marrett and Allmendinger, 1990). Slip on each fault can be viewed as contributing an incremental shear strain to the overall volume of the fault zone. The directions of maximum shortening and maximum extension associated with this incremental strain will bisect the slip direction and the normal to the fault surface. In this sense, the principal strain directions are analogous to pressure and tension axes used to determine focal-plane solutions in seismology. Because the deformation is finite and involves internal rotations, it is preferable to view these axes as representing strain, not stress. The principal strain directions for the fault zone are estimated by contouring the axes for the individual faults. Proper integration of bulk brittle strain would require weighting each measurement proportional to the amount of slip on the fault. Slip magnitude is usually estimated indirectly by use of an empirical scaling relation that relates fault slip to fault length or gouge thickness. We have given equal weight to each fault because there is a limited variation in size among the exposed faults. Relating the estimated principal directions for bulk brittle strain to the overall direction of slip for the fault zone is straightforward as long as the fault zone is the result of a single-stage history and the measured structures are representative of the total population of faults that make up the fault zone.

Observations

The two fault zones we studied consist of tabular zones of highly faulted serpentinite, about 3–4 km thick, which are directly bounded by rocks of the eastern Franciscan in the footwall and the Coast Range ophiolite in the hanging wall. Individual blocks in the fault zone are angular, are composed of variably serpentinitized harzburgite, and are separated by thin, well-polished slickensides with remarkably well developed striae and a paucity of fault gouge. The striae are constructional features composed of fibrous serpentine that grew adjacent to moving asperities on the fault surface (cf. Suppe, 1985). In this case, we would expect a fairly complete record of fault slip to be preserved. The sense of slip can be deduced by the direction of fiber growth and by small steps in the fibers formed by tensile fractures oriented perpendicular to the fault surface and the slip direction. Fibers on each slickenside are, in almost all cases, straight and uniformly oriented, indicating a single phase of motion within the studied fault zones (a local exception is noted below). The population of slip directions is also consistent from outcrop to outcrop and between the two study areas, which further supports our interpretation of a simple, single-stage slip history.

In the Beehive Flat area of the Yolla Bolly Mountains, we measured structural data for 170 fault surfaces in seven large roadside outcrops covering a distance of 8 km perpendicular to the fault zone and representing 950 m^2 of outcrop. Fault density ranges from five to 21 faults per metre. When viewed in present coordinates, 84% of the faults show a dip-slip sense of motion directed mostly to the west (96 out of 143), but also to the east (47 out of 143). Most of these faults (117 out of 143) would be classed as normal faults. The remaining 16% are either sinistral (nine out of 27) or dextral (18 out of 27) strike-slip faults.

In Del Puerto Canyon of the Diablo Range, we measured 70 faults in four areas that cover a distance of 3.5 km across the fault zone and represent 200 m^2 of outcrop. Fault density is on the order of five to 17 faults per metre. Like Beehive Flat, only one dominant set of straight fibers is typically present. However, five fault surfaces have a superimposed set of subhorizontal striae, which we attributed to late Cenozoic strike-slip deformation known to occur on the Hayward and Calaveras faults, which flank the Diablo Range uplift (Fig. 2). These slip data are not included in our analysis here. In present coordinates, 79% of the faults have a dip-slip sense of motion directed generally to the west (38 out of 55) but also to the east (17 out of 55). Most of these faults (44 out of 55) would again be classed as normal faults. The remaining 21% are sinistral and dextral strike-slip faults, in equal proportions.

Analysis

The contoured shortening directions for all sampled faults in the Beehive Flat area (Fig. 3A) show a well-defined point maximum oriented in a subvertical direction, subparallel to the present down-dip direction of the fault (great circles in Fig. 3 indicate fault-zone orientation). The contoured extension axes (Fig. 3B) show a girdle pattern; a maximum, however, is apparent and has a subhorizontal direction trending east-southeast (110°). Because the present steep dip of the Coast Range fault is generally considered to postdate the formation of the fault, it is useful to view the data in a fault-parallel reference frame, with the primitive circle of the stereogram oriented parallel to the regional attitude of the fault zone. The data are transformed by rotation around the regional strike of the fault zone. This reference frame emphasizes the fact that the shortening axes now lie subparallel to the fault zone (Fig. 3C), indicating crustal shortening in a northeast (70°) subhorizontal direction. Furthermore, those faults with normal geometry in present coordinates apparently originated as reverse faults, dipping mainly to the east.

At Del Puerto Canyon, the contoured shortening and extension directions (Fig. 3, E and F) show nearly identical relations, although the extension axes display a better developed point maximum. In a fault-parallel reference frame, the data also indicate fault-parallel shortening (Fig. 3G) in a northeast (55°) subhorizontal direction. Those faults with normal geometry in present coordinates apparently originated as mainly east dipping reverse faults, as indicated when viewed in a fault-parallel reference frame.

Deformation within the Coast Range fault zone appears to have been characterized by distributed reverse faulting. No one has been able to identify a dominant fault structure within the zone. Therefore, we conclude that our measurements at the outcrop scale are representative of the regional-scale brittle strain, which appears to be contractional in the plane of the fault zone.

TECTONIC IMPLICATIONS

As discussed above, the traditional model (e.g., Ingersoll, 1979) (Fig. 4A) for the tectonic evolution of the Franciscan complex does not account for the metamorphic break at the Coast Range fault. The extensional model (e.g., Platt, 1986) postulates that the metamorphic break is due to extensional faulting. Our kinematic data provide no evidence of fault-parallel extension; instead, data indicate that brittle deformation within the fault zone was dominated by fault-parallel contraction.

We focus here on two viable models, the tectonic wedge model of Wentworth et al. (1984) (Fig. 4C) and the thin-skinned model of Suppe (1979) (Fig. 4D). Both models attribute the structure of the Franciscan–Great Valley contact to younger out-of-sequence thrust faults. Both are compatible with fault-parallel contraction on the Coast Range fault, the metamorphic break at the fault, and the substantial thinning of the Coast Range ophiolite. For the thin-skinned

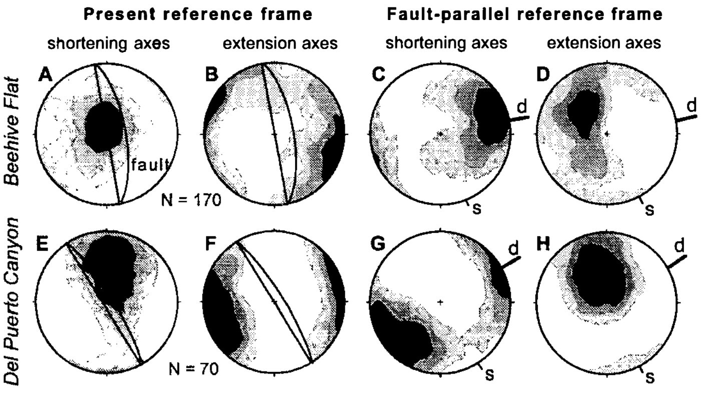

Figure 3. Contoured maximum-shortening and maximum-extension axes for brittle strain at Beehive Flat and Del Puerto Canyon. Regional strike, s, and down-dip direction, d, of fault zone are shown. Diagrams are synoptic; there is no evidence of structural domains. Contours are according to Kamb (1959) and are in multiples of uniform density starting at 1, with interval of 0.66.

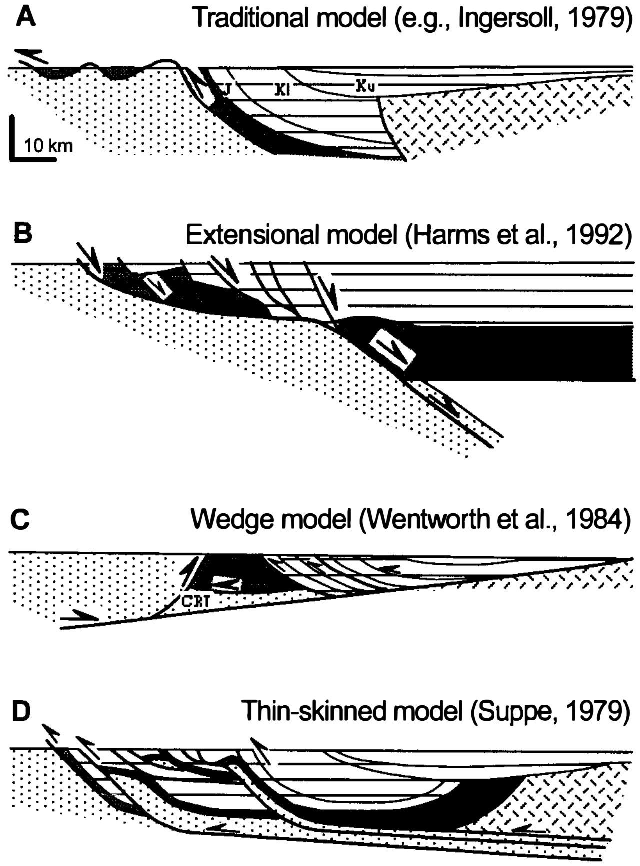

Figure 4. Four models of tectonic evolution of Franciscan complex. Symbols and patterns as in Figure 2, except for Franciscan, which is stippled and undivided. A: Traditional model showing original configuration of Cretaceous convergent margin. Fore-arc massif is thrust onto Franciscan complex. B: Extensional model explaining contact of Franciscan complex and Great Valley Group by Late Cretaceous–early Tertiary top-side-east normal faults. C: Coast Range ophiolite as part of Cretaceous tectonic indenter that wedged eastward between overlying Great Valley sequence and Sierran arc. Coast Range fault is interpreted to be top-side-east out-of-sequence thrust fault that postdated and obscured original subduction-related structure of margin. D: Model of Cenozoic west-vergent, out-of-sequence thrust faults.

model, the metamorphic section must have already been tilted to the east, indicating that the Eastern Franciscan was already located in a structurally high position within the wedge, presumably a result of sustained basal accretion beneath the Franciscan wedge.

Our principal conclusion is that the Coast Range fault formed as an out-of-sequence thrust fault, either by backthrusting (wedge model) or by forward thrusting (thin-skinned model). Whereas slip on an out-of-sequence fault can account for the break in metamorphic grade at the Coast Range fault, it cannot account for exhumation of metamorphic rocks in the footwall of the fault. The reason is that while the fault can cause thinning in a tilted metamorphic section, it will still produce thickening in the vertical direction, resulting in structural burial of rocks in the footwall.

Therefore, we conclude that the eastern Franciscan was exhumed mainly by erosion. Fission-track data (Dumitru, 1989) show that exhumation of the Franciscan complex occurred over a long period of time, which is compatible with erosional denudation of an emergent accretionary wedge. Assuming a plausible erosion rate of 1 mm/yr, the blueschist facies rocks, which were metamorphosed at ~30 km at about 90 Ma, would reach the surface by 60 Ma. The argument against this interpretation is that adjacent sedimentary basins, such as the Great Valley Group, show no evidence of erosional unroofing of high-pressure metamorphic rocks (e.g., Platt, 1986). However, the record of this event would probably be fairly cryptic because the eroded section would have been dominated by the higher level rocks of the Franciscan wedge, including the Great Valley Group, Coast Range ophiolite, and low-grade sedimentary rocks of the subduction complex.

A modern analogue for deep erosional exhumation of an active subduction wedge is the Olympic Mountains (Fig. 2, inset). Brandon and Vance (1992) showed that the mountainous topography that overlies the fore arc of the Cascadia subduction zone grew from sea level over the past 12 m.y. due to underplating and within-wedge thickening. Erosional exhumation has removed about 12 km of rock, and if the system continues in its present form, a level equivalent to the present exposed depth of the eastern Franciscan will be exposed 12 m.y. from now. We note that most of the eroded material coming from the Olympics uplift is carried by west-draining rivers because precipitation is much greater there. The eastern side of the uplift is less well drained, so only a small fraction of eroded rock is deposited in the modern Cascadia fore-arc basin (Puget Sound). This analogue example suggests that sediments from an erosionally denuded Franciscan might be found in trench and trench-slope sediments that were accumulating seaward of the Franciscan at that time. Cowan and Page (1975) described evidence of detritus from high-pressure metamorphic rocks in what are interpreted as trench and trench-slope sediments, but at this time it is not possible to estimate the volume of eroded sediment that might be present in these types of deposits.

CONCLUSIONS

Kinematic data for the Coast Range fault indicate a history of fault-parallel contraction. We propose that the Coast Range fault as now exposed is an out-of-sequence fault that attentuated an already tilted metamorphic sequence, thus explaining the pronounced break in metamorphic grade across this fault. We stress that an abrupt downward increase in metamorphic grade, and also the presence of stratigraphically younger over older rocks, can be produced during overall contractional deformation and is not a unique indicator of extensional faulting. Kinematic data are critical for elucidating the slip history of a fault zone.

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Reviewer's comment

Addresses a major tectonic problem with wide implications for the dynamics of mountain belts and accretionary wedges.

John P. Platt