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Deformation of the Eastern Franciscan Belt, northern California

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Abstract—The late Jurassic and Cretaceous Eastern Franciscan belt of the northern California Coast Range consists of two multiply deformed, blueschist-facies terranes; the Pickett Peak and Yolla Bolly terranes. Four deformations have been recognized in the Pickett Peak terrane, and three in the Yolla Bolly terrane. The earliest recognized penetrative fabric, D_1, occurs only in the Pickett Peak terrane. The later penetrative fabrics, D_2 and D_3, occur in both the Yolla Bolly and Pickett Peak terranes. D_1 and D_2 apparently represent fabrics that formed during subduction and accretion of the terranes. Fabrics from both D_1 and D_2 are consistent with SW–NE movement directions with respect to their present geographic positions. D_3 postdates blueschist-facies metamorphism of the terranes and may be related to emplacement of the terranes to higher structural levels. A broad regional warping, D_4, is evident from the map pattern and folding of large metamorphosed thrust sheets. D_4 folds may be related to deformation associated with oblique convergence along the continental margin in late Cretaceous and (or) early Tertiary time.

INTRODUCTION

THE Franciscan Complex has long been interpreted as a subduction complex that formed in a trench slope environment adjacent to a late Mesozoic Andean-type continental arc (Hamilton 1969, Ernst 1970). North of the San Andreas fault, the Franciscan Complex consists of three generally NW-trending belts of rock: (1) an early Tertiary broken formation, the Coastal Franciscan belt; (2) a tectonic melange, the Central Franciscan belt; and (3) a regionally metamorphosed blueschist-facies belt, the Eastern Franciscan belt (Irwin 1960, Bailey *et al.* 1964, Berkland *et al.* 1972) (Fig. 1). In the northern Coast Ranges, the blueschist-facies rocks of the Eastern Franciscan belt have been the subject of numerous studies (Ghent 1965, Blake *et al.* 1967, 1981, Wood 1971, Suppe 1973, Bishop 1977, Maxwell *et al.* 1981, Worrall 1981, Blake & Jayko 1983, Brown & Ghent 1983, Jayko *et al.* 1986) which are gradually shedding light on the complex metamorphic and tectonic evolution of this region.

We herein describe the deformational state of the Eastern Franciscan belt and in particular contrast the structural characteristics of the two major tectonic units within the Eastern Franciscan belt: the Pickett Peak and Yolla Bolly terranes. Detailed structural descriptions of blueschist-facies rocks are few, and the general structural coherence of the Eastern Franciscan belt has not been emphasized relative to the chaotic nature of the Central Franciscan belt melange for which the Franciscan Complex is best known (e.g. Hsu 1971).

Eastern Franciscan belt rocks east of the San Andreas fault are distributed from the Diablo Range in northern California to Roseburg in southwestern Oregon (Blake *et al.* 1982, Silberling *et al.* 1984) (Fig. 1). They also occur as tectonic slabs within the Central Franciscan belt (Irwin 1960, Blake & Jones 1974, Monson & Aalto 1980, Maxwell *et al.* 1981, McLaughlin & Ohlin 1984, Blake *et al.* 1985, Cashman *et al.* 1986) (Fig. 1).

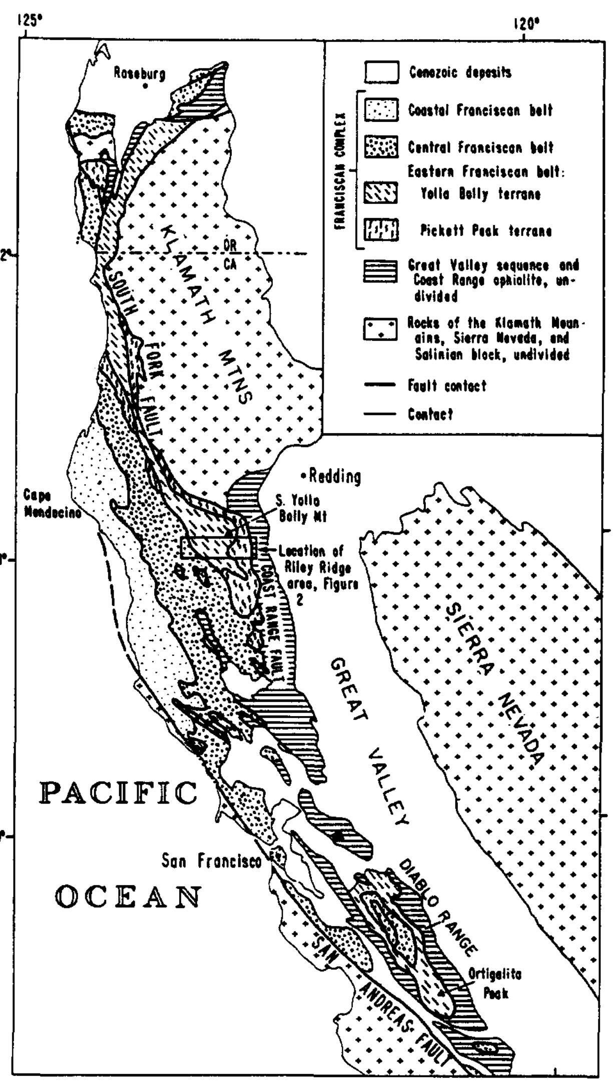


Fig. 1. Generalized tectonic map showing location of the Coastal, Central and Eastern belts of the Franciscan Complex and the location of the study area, modified from Silberling *et al.* (1984).

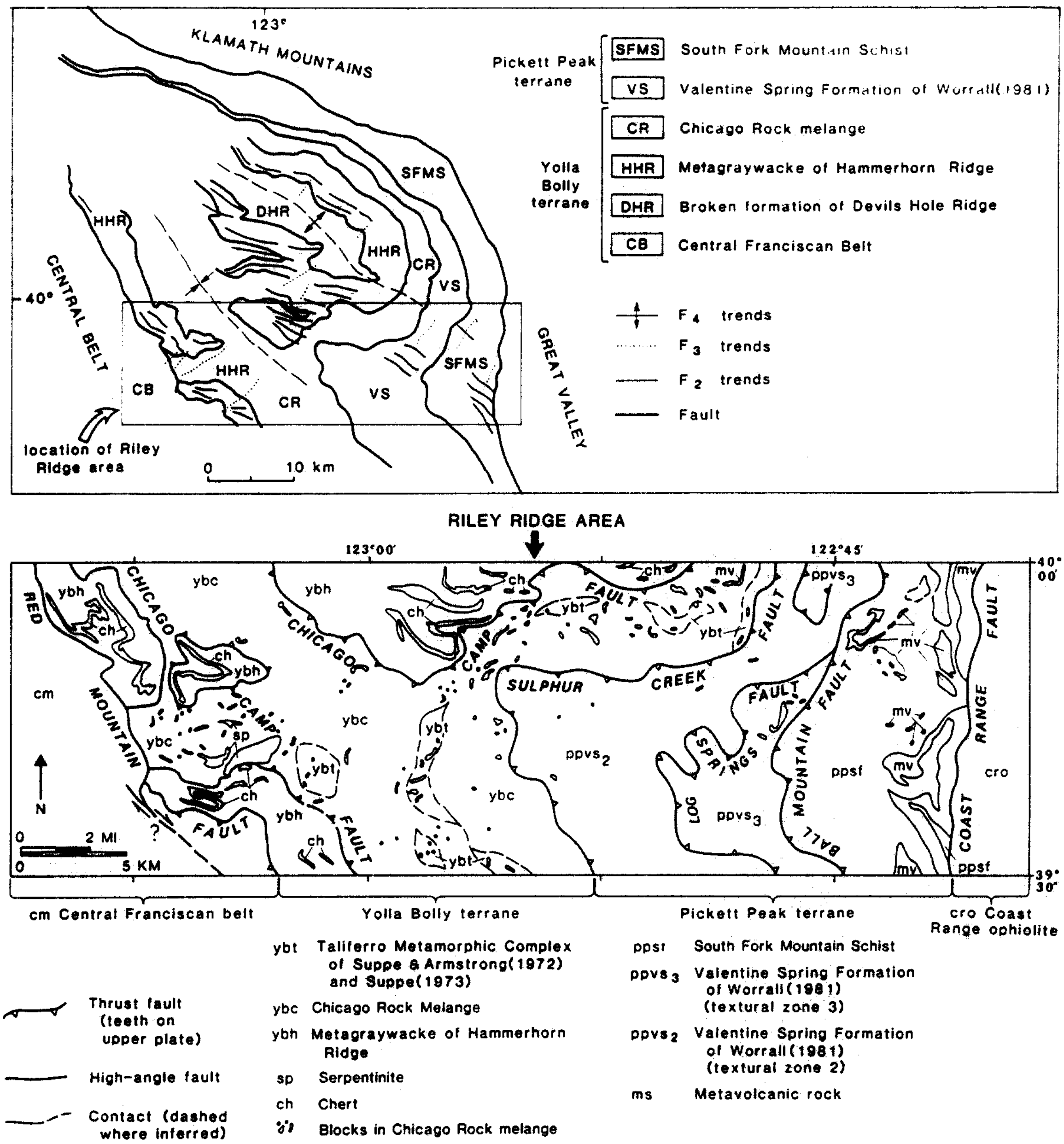


Fig. 2. Generalized geologic map with location of Riley Ridge area in Eastern belt of the Franciscan Complex. Structural trends compiled from Blake (1965), Worrall (1981), this study and unpublished reconnaisance mapping by Blake and Jayko.

The boundary between the Eastern Franciscan belt and Central Franciscan belt is principally an E-dipping, low-angle thrust that has been extensively modified by late Cretaceous and/or Cenozoic high-angle faults (Blake & Jayko 1983, Jayko 1983, Blake *et al.* 1985). The Eastern Franciscan belt is bounded on the east against the Coast Range ophiolite along the Coast Range fault (Bailey *et al.* 1970, Jayko & Blake 1986), and bounded on the northeast against Klamath basement along the South Fork fault (Irwin *et al.* 1974, Kelsey & Hagan 1982).

GENERAL GEOLOGY

The Eastern Franciscan belt consists of two major units, the Pickett Peak and Yolla Bolly terranes (Figs. 1 and 2), which are juxtaposed along an E-dipping, low-angle fault. The structurally higher terrane, the Pickett Peak terrane, consists of two fault-bound units, the metagraywacke-dominated Valentine Spring Formation of Worrall (1981) (Fig. 2) and the structurally overlying quartz–mica schist and Chinquapin Metabasalt Member of the South Fork Mountain Schist (Blake *et al.* 1967). The Pickett Peak terrane has been interpreted as a fragment of a seamount province or oceanic plateau overlain by a continentally derived clastic sequence (Jayko 1984). These rocks were apparently scraped off subducting oceanic lithosphere at the North American continental margin and metamorphosed during the early Cretaceous, as indicated by K–Ar, Ar^{40}–Ar^{39} and Rb–Sr whole rock ages which range between 110 and 142 Ma (Suppe 1973, Lanphere *et al.* 1978, McDowell *et al.* 1984) (Fig. 3).

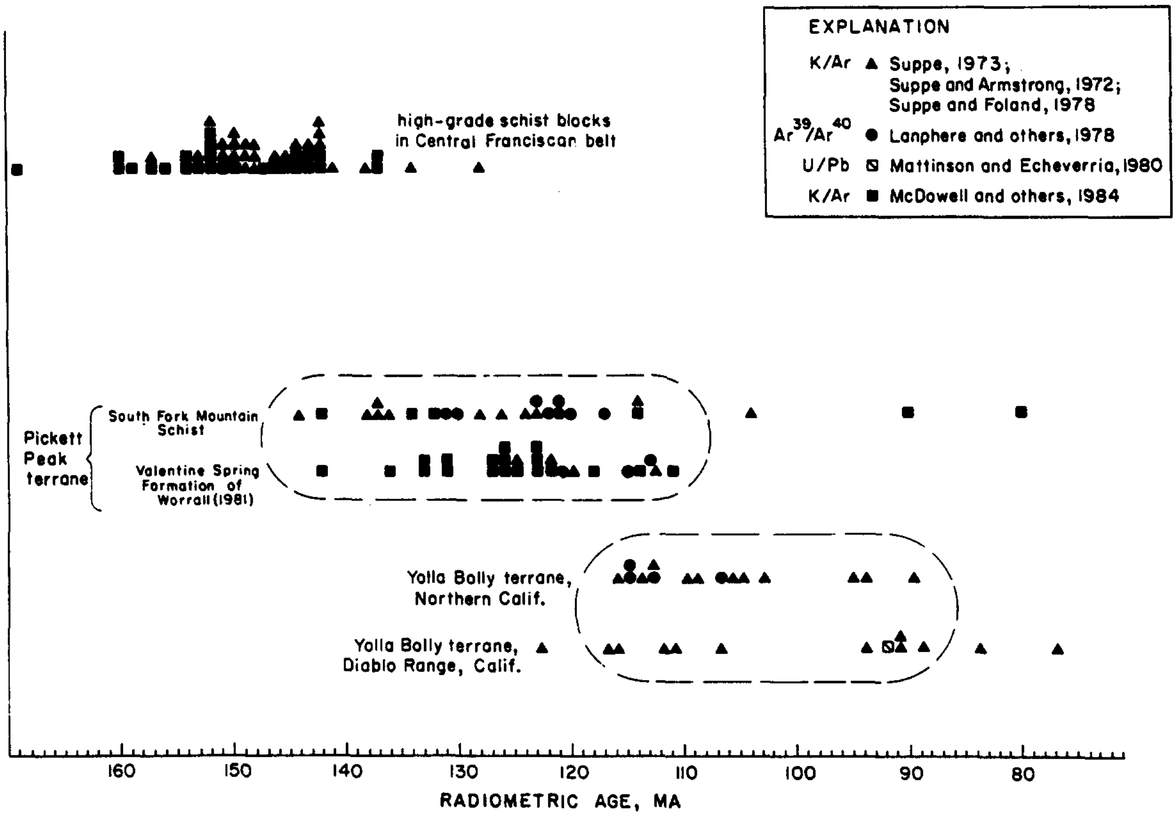


Fig. 3. Radiometric age dates from Eastern belt of the Franciscan Complex and high-grade blocks in Central and Eastern Franciscan belts.

Structurally beneath the Pickett Peak terrane is the Yolla Bolly terrane, which consists of four tectonic units: Chicago Rock melange, the metagraywacke of Hammerhorn Ridge, the broken formation of Devils Hole Ridge (Blake & Jayko 1983), and the Taliaferro Metamorphic Complex (Suppe & Armstrong 1972, Suppe 1973). Graywacke in the Yolla Bolly terrane is micaceous lithic quartzo-feldspathic in composition. Detrital quartz, albite, biotite, white mica, epidote and zircon indicate a continental provenance.

The Chicago Rock melange, the structurally highest unit, consists of tectonized argillite and metagraywacke, with intercalated, thin-bedded radiolarian chert, minor greenstone and scarce irregular bodies of serpentinite. Rare blocks of 150–164 Ma (Suppe 1973, Mattinson 1981, 1986) amphibolite and coarse-grained mafic blueschist are located near the serpentinite bodies. Introduction of these blocks into the Chicago Rock melange was probably facilitated by serpentinite migration along faults that juxtaposed the Yolla Bolly and Pickett Peak terranes and imbricated the Yolla Bolly terrane. Intermixed with the Chicago Rock melange are many slabs and thin thrust sheets of the Taliaferro Metamorphic Complex (Suppe 1973) that are of slightly higher grade than the surrounding argillaceous matrix. The Taliaferro Metamorphic Complex, as defined in this study, includes the jadeite- and blue amphibole-bearing metagraywackes and cherts of Suppe (1973) but excludes the older blocks of coarse-grained blueschist and amphibolite dated at approximately 160 Ma.

The Hammerhorn Ridge unit, a massive metagraywacke with a continuous horizon of interlayered radiolarian chert, structurally underlies the Chicago Rock melange. The interbedded chert and metagraywacke of the Hammerhorn Ridge unit and Taliaferro Metamorphic Complex are locally intruded by Ti-rich alkalic gabbro sills and dikes. Igneous rocks that occur as dikes and extrusive flows in the Chicago Rock and Hammerhorn Ridge units have yielded bimodal silica contents that range from 45–51% to 68–73% SiO_2 (Jayko 1984). The Devils Hole Ridge unit consists of deformed graywacke and argillite that structurally underlies the Hammerhorn Ridge unit north of this study area. The Chicago Rock melange, Hammerhorn Ridge unit, Devils Hole Ridge unit and deeper seated equivalent Taliaferro Metamorphic Complex are inferred to be lateral facies equivalents. The micaceous lithic quartzo-feldspathic strata were apparently deposited along the continental margin. The occurrence of alkalic bimodal igneous rock that intrudes and interfingers with the clastic deposits suggests that the margin was undergoing minor extension probably associated with oblique convergence (Blake *et al.* 1981).

Radiolarian microfossils and rare *Buchia* megafossils indicate a late Jurassic and early late Cretaceous protolith age for units in the Yolla Bolly terrane (Suppe 1973, Worrall 1981, Blake *et al.* 1985). The Yolla Bolly terrane was imbricated and metamorphosed during mid-Cretaceous time (Blake *et al.* 1985). K–Ar whole-rock analyses from metasedimentary rocks yield predominantly 90–115 Ma ages (Suppe 1973, Lanphere *et al.* 1978) which may represent the time of subduction and accretion of the Yolla Bolly terrane to the continental margin.

METAMORPHISM

Rocks of the study area show a progressive west-to-east increase in metamorphic grade (Blake *et al.* 1967, 1988, Suppe 1973, Worrall 1981, Jayko *et al.* 1986). Three isograds can be recognized within the Pickett Peak terrane of the Eastern Franciscan belt (Jayko *et al.* 1986). Here the term 'isograd' is used, purely in a descriptive sense, as the first or last occurrence of a phase, because numerous faults disrupt a true prograde sequence. Clastic metasedimentary rocks show blue amphibole-in and paragonite-in isograds, and *in situ* metavolcanic rocks show a lawsonite-out isograd (Jayko *et al.* 1986).

In addition to the appearance and/or disappearance of index minerals, the relative abundance of some phases varies considerably. For example, in the Pickett Peak terrane, blue amphibole typically constitutes 30–60% of the mafic metaigneous rock, whereas in the Yolla Bolly terrane, blue amphibole, if present, commonly constitutes only about 1% or less of the *in situ* metaigneous rock (Jayko *et al.* 1986). Lawsonite occurs throughout the study area in clastic metasedimentary rocks, its grain size and abundance increasing considerably toward the east. Pumpellyite is also widespread in metavolcanic rocks throughout the study area, but in metagraywacke it is generally restricted to the Yolla Bolly terrane. Both pumpellyite and celadonite commonly occur in low-grade, non-schistose metagraywacke, but not in higher grade, strongly foliated metagraywacke.

Metagraywacke of the Eastern Franciscan belt is also characterized by a variable development of penetrative cleavage or schistosity. The criterion for determining textural reconstitution was first developed by Hutton & Turner (1936) for quartzo-feldspathic lithic graywackes in New Zealand and was later applied to Franciscan rocks by Blake *et al.* (1967), Suppe (1973), Bishop (1977) and Worrall (1981). The textural zones in the Eastern Franciscan belt are: TZ 1, which is characterized by no obvious flattening in thin section and no preferred orientation or foliation; TZ 2A, which has an anastomosing schistosity; TZ 2B, which has a planar parallel schistosity; and TZ 3, which is characterized by gneissic banding and quartz–albite segregations thicker than 2 mm (Blake *et al.* 1967, Jayko *et al.* 1986).

Both the mineral assemblages and textural fabric, particularly within the Pickett Peak terrane, suggest increasing metamorphic and deformational conditions from west to east, and from structurally low to structurally high in the section, as recognized by previous workers (Blake *et al.* 1967, Suppe 1973, Worrall 1981).

STRUCTURE

Multiple phases of deformation can be recognized in both the Pickett Peak and Yolla Bolly terranes (Table 1). Four phases are present in the Pickett Peak terrane, two with well developed foliation accompanying blueschist-facies metamorphism (D_1 and D_2), one with a weakly developed crenulation cleavage (D_3), and the last, with a broad open regional warping (D_4). Three phases (D_2, D_3, D_4) are present in the Yolla Bolly terrane.

The various phases of folding are distinguished in the field on the basis of differences in the morphology and orientation of the foliation and folds. The S_1 foliation in the Pickett Peak terrane is axial planar to F_1 and is characterized by segregation layering in the higher grade metasedimentary rocks and a pervasive spaced cleavage (cleavage terminology after Powell 1979) in TZ 2B metagraywacke. F_1 folds are tight to isoclinal and commonly parallel to L_1 amphibole lineations. Blue amphiboles form a pronounced lineation in metachert and metavolcanic rock similar to that described from other blueschist terranes (for example, Malavieille *et al.* 1984).

The F_2 folds in the Pickett Peak terrane are tight to open, usually asymmetric, with axial planes dipping to the southwest and fold hinges and strikes of axial planes trending NW–SE. In metagraywacke of the Yolla Bolly terrane, the S_2 foliation is a micro-stylolitic to a smooth, disjunctive, spaced cleavage with random to strong microlithon fabric alignment. F_2 folds in the Yolla Bolly terrane are usually tight to isoclinal.

The S_3 foliation in both terranes is a discrete crenulation cleavage that is less well developed than S_2 and usually oriented at a high angle to S_2. F_3 folds are commonly kink or box shaped and less commonly concentric, with axial planes striking NE–SW and dipping to the NW or SE, and hinges plunging NE or SW. North of the study area, F_3 folds have a pronounced asymmetry and are consistently overturned to the ESE (Blake 1965).

The F_4 phase of folding is inferred from the regional map pattern. Obvious small-scale structures associated with this folding are rare in outcrop or thin section, although a few late asymmetric chevron folds oriented subparallel to the regional trend of the F_4 structures were observed in the field. Table 1 summarizes the general characteristics of the D_1–D_4 deformation phases.

D_1 *structures*

D_1 was observed only within the Pickett Peak terrane where it is characterized by rare tight to isoclinal folds (F_1) and segregation of metamorphic quartz and albite vs white mica, chlorite and lawsonite (S_1). The segregation layering appears to parallel the relict argillaceous layers in the more coherent metagraywacke. The metamorphic minerals are very fine grained, usually less than 0.3 mm. The tabular minerals white mica, chlorite and lawsonite commonly show strong preferred crystallographic orientation with the lawsonite (010), and mica and chlorite (001) faces subparallel to S_1. In the quartz–albite layers the foliation is defined by at least three features: (1) the dispersed fine-grained, strongly

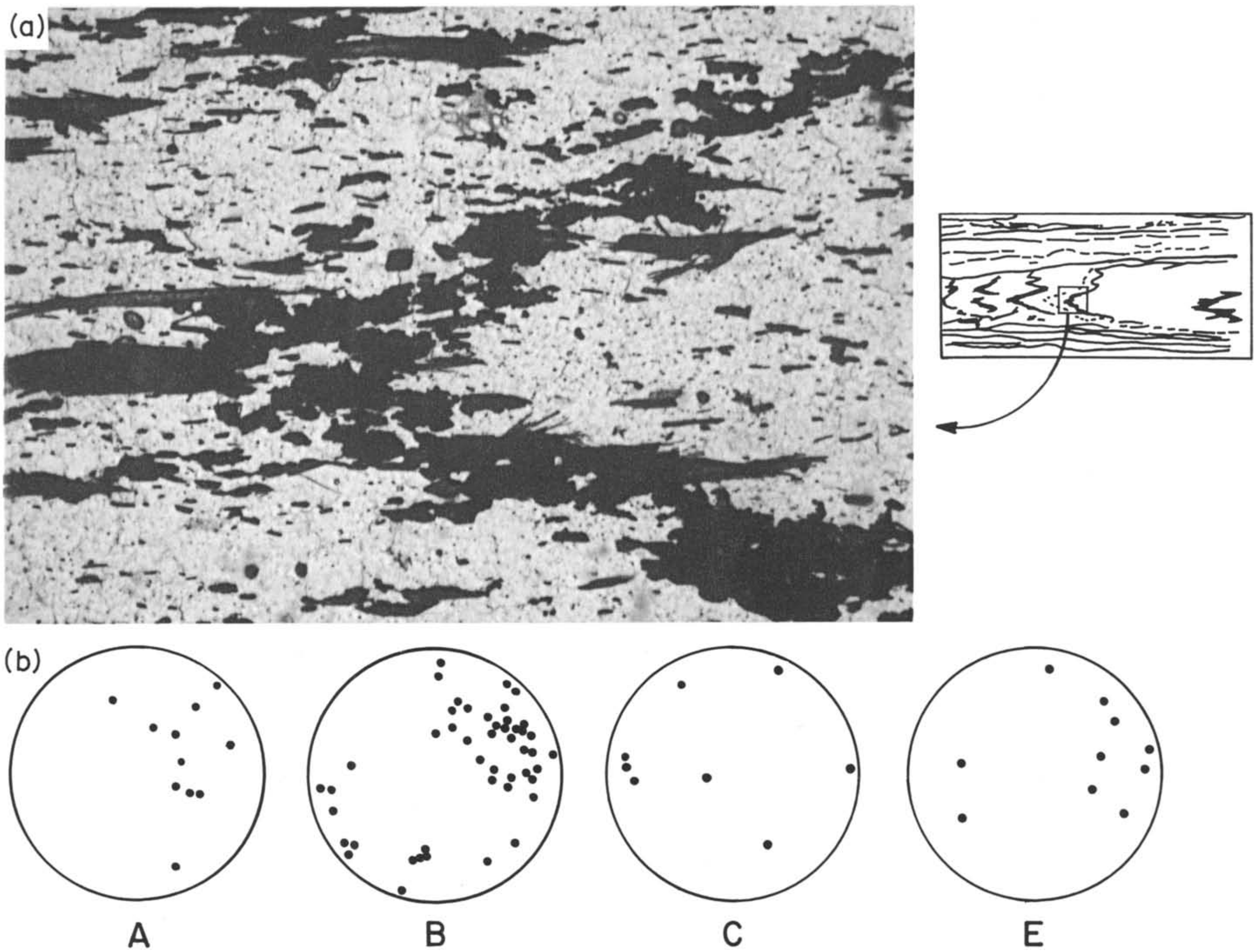
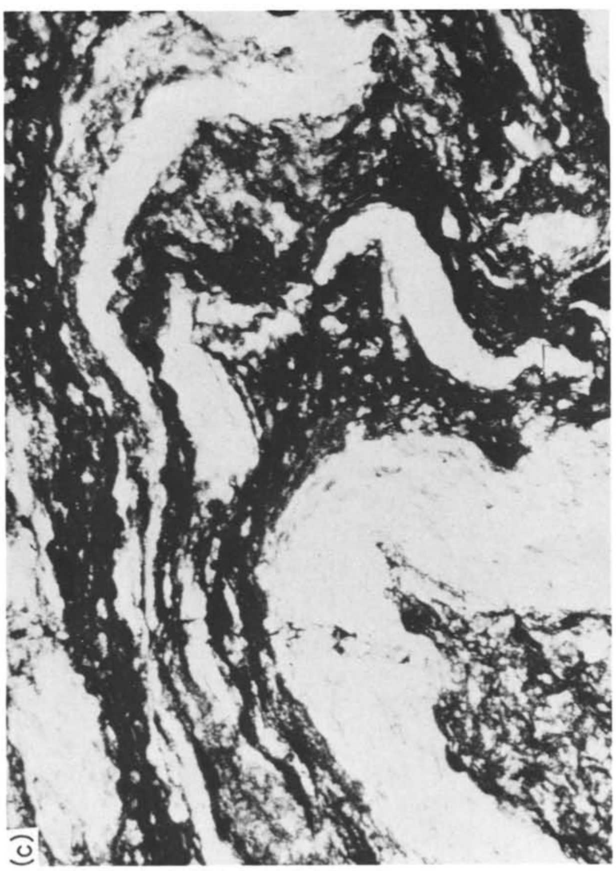


Fig. 4. (a) F_1 fold hinge in metachert of the South Fork Mountain Schist. Dark minerals are crossite and magnetite (width of photo approximately 3 mm). Adjacent to photomicrograph is a 1:1 drawing of thin section showing parallel limbs of isoclinal fold. (b) Stereonet plot of L_1 blue amphibole lineations from the Pickett Peak terrane (equal-area, lower-hemisphere projection). See Fig. 5 for location of structural subareas. *Overleaf.* (c) F_2 fold deforming S_1 and F_1 in mica schist of the Pickett Peak terrane (width of photo approximately 3 mm). (d) Asymmetric F_2 folds in mica schist of the Pickett Peak terrane. (e) F_3 conjugate fold pair in chert of the Yolla Bolly terrane. (f) Photomicrograph of F_3 folds in the South Fork Mountain Schist.


(c)


(d)
DECIMETER


(e)


(f)

Table 1. Summary of structures related to D_1–D_4

	D_1	D_2	D_3	D_4
		Pickett Peak terrane		
Folds	(F_1) Isoclinal-tight	(F_2) Tight to open	(F_3) Open-conjugate chevron, box	(F_4) Open warping (Yolla Bolly antiform)
Axial planes	(S_1) Refolded	(S_2) SW dip	(S_3) Steep SE–NW and refolded	(S_4) Nearly dipping vertical
Fabric	Mineral segregation into bands up to 3–4 mm in metasedimentary rock and poorly defined layering metaigneous rock	Strong transposition of S_1, S_2 development of crenulation cleavage	Crenulation cleavage	No penetrative fabric
Lineations	(L_1) Dispersed mineral and streaking most abundant	(L_2) Variable but SE and NW, intersection	(L_3) NE–SW fairly well grouped, intersection	?
Asymmetry	—	SW–NE vergence in Valentine Spring	Variable, but vergence is SE north of study area	SW limb of regional antiform is overturned locally
		Yolla Bolly terrane		
Folds	—	(F_2) Isoclinal-tight	(F_3) Tight to open	(F_4) Open
Axial planes	—	(S_2) Predominantly SW dipping	(S_3) Steep NW–SE dipping	(S_4) Nearly vertical?
Fabric	—	Weak to strong schistosity, flattening and elongation of clasts	Poorly developed crenulation cleavage only local	Brittle deformation
Lineations	—	(L_2) Predominantly SE–S	(L_3) Predominantly SW	Plunging
Asymmetry	—	Not noticeable; notably verging to SW north of study area	SW–NW, NW–SE north of study area	Like D_4 in Pickett Peak terrane

oriented phyllosilicates and lawsonite; (2) the mineral segregation layers; and (3) variation in grain size of quartz and albite parallel to mineral segregation layers. In Chinquapin metabasalts, S_1 is formed by preferred orientation of metamorphic minerals and mineral segregation layers. Where segregation layering is absent, the foliation planes are usually very closely spaced, approximately 0.5 mm apart, and defined by wispy zones of opaques commonly altered to sphene.

Small-scale F_1 folds are usually difficult to find in outcrop and hand specimen. F_1 fold styles, orientations, and the relationship between F_1 and F_2 folds and schistosity are shown in Figs. 4(a) & (c). L_1 lineations include striping defined by S_0–S_1 low-angle intersections, preferred crystallographic orientation of blue amphibole in metavolcanic rocks and metacherts (Fig. 4b), and rare F_1 hinges. In nearby areas, L_1 includes smearing out of plagioclase phenocrysts, pillows and pillow breccias (Blake 1965, Bishop 1977). The L_1 mineral lineations show considerable scatter; however, they tend to be concentrated in the NE quadrant and are interpreted to indicate the general transport direction.

D_2 *structures*

D_2 is observed both in the Pickett Peak terrane where it is the second deformation and in the Yolla Bolly terrane where it is the first deformation. In both terranes, D_2 is commonly accompanied by the development of a new schistosity, asymmetric folds and blueschist-facies metamorphism. Both terranes show a consistent orientation of folds associated with D_2.

The S_2 foliation in metagraywacke of the Pickett Peak terrane is typically a discrete crenulation cleavage. In the Yolla Bolly terrane it is a disjunctive spaced cleavage. In rocks of the Pickett Peak terrane, S_2 is well developed and locally completely transposes S_1. Domains of strong S_2 transposition in the Pickett Peak terrane probably represent axial zones of folds that cannot be mapped on a regional scale due to the absence of local marker horizons. S_2 is most strongly developed in mica schist of the Pickett Peak terrane where it is usually the prominent schistosity and transposes the segregation layering. In metagraywacke, S_2 is always present but secondary to S_1, and in metavolcanic rocks it is often difficult to observe, except within hinge zones, as it forms only a faint crenulation cleavage in the more massive rocks. S_2 differs from S_1 in the Pickett Peak terrane in that it is characterized by the crystallization of new metamorphic white mica and chlorite along the crenulation surfaces but lacks the development of segregation layering that typifies S_1. S_2 is more easily recognized in the Yolla Bolly terrane because it represents the first penetrative deformational fabric. Note that S_2

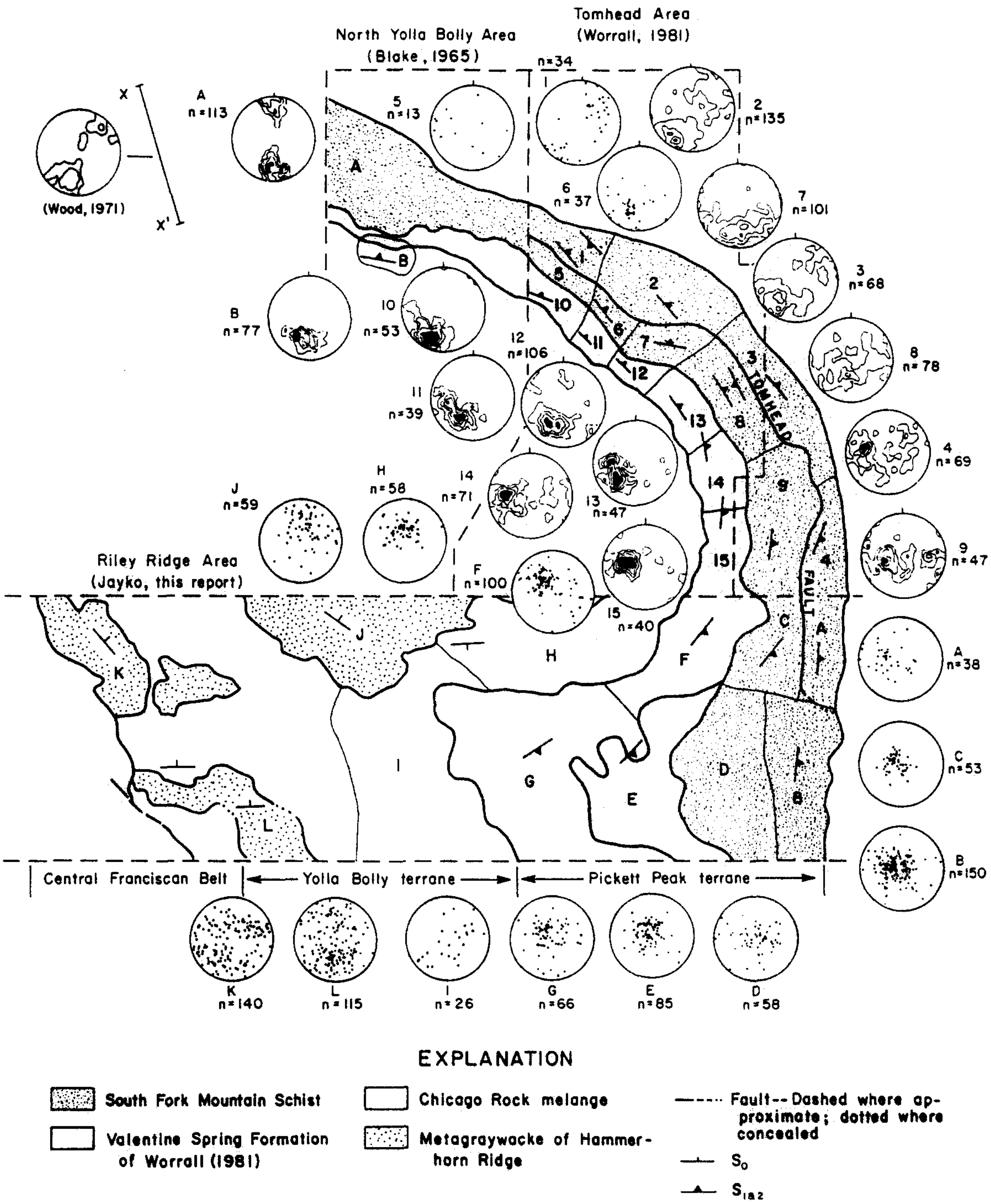


Fig. 5. Map showing distribution of structural subareas and corresponding equal-area stereonet plots of poles to foliation where foliation symbol shown, or poles to bedding where bedding symbol shown. Structural data from outside the study area are compiled from Blake (1965) and Worrall (1981). Cross-section X–X' is from Wood (1971).

that S_2 denotes the earliest deformation fabric in the Yolla Bolly rocks but formed during the D_2 regional event, and is named S_2.

The orientation of S_1 and S_2 foliation in both the South Fork Mountain Schist and Valentine Spring Formation is variable; however, there are a few patterns that emerge from the stereonet plots (Fig. 5). Dips are generally shallow (45° or less) and east or southeast dipping in the Riley Ridge area. Further north, the dip of S_1 and S_2 schistosity changes to northeasterly in the Tomhead area (Worrall 1981) to predominantly northerly in the Black Rock Mountain–North Yolla Bolly area (Blake 1965).

Small-scale F_2 folds are common and can be found in most mica schist outcrops. The folds are open to tight, rarely isoclinal, and usually asymmetrical with a variable sense of overturning (Fig. 4d). In the Riley Ridge area, poles to axial planes (Fig. 6), show a strong clustering in the NE quadrant, indicating predominantly SW-dipping axial planes.

F_2 hinges scatter due to their superposition on earlier structures and later refolding, but show concentration in

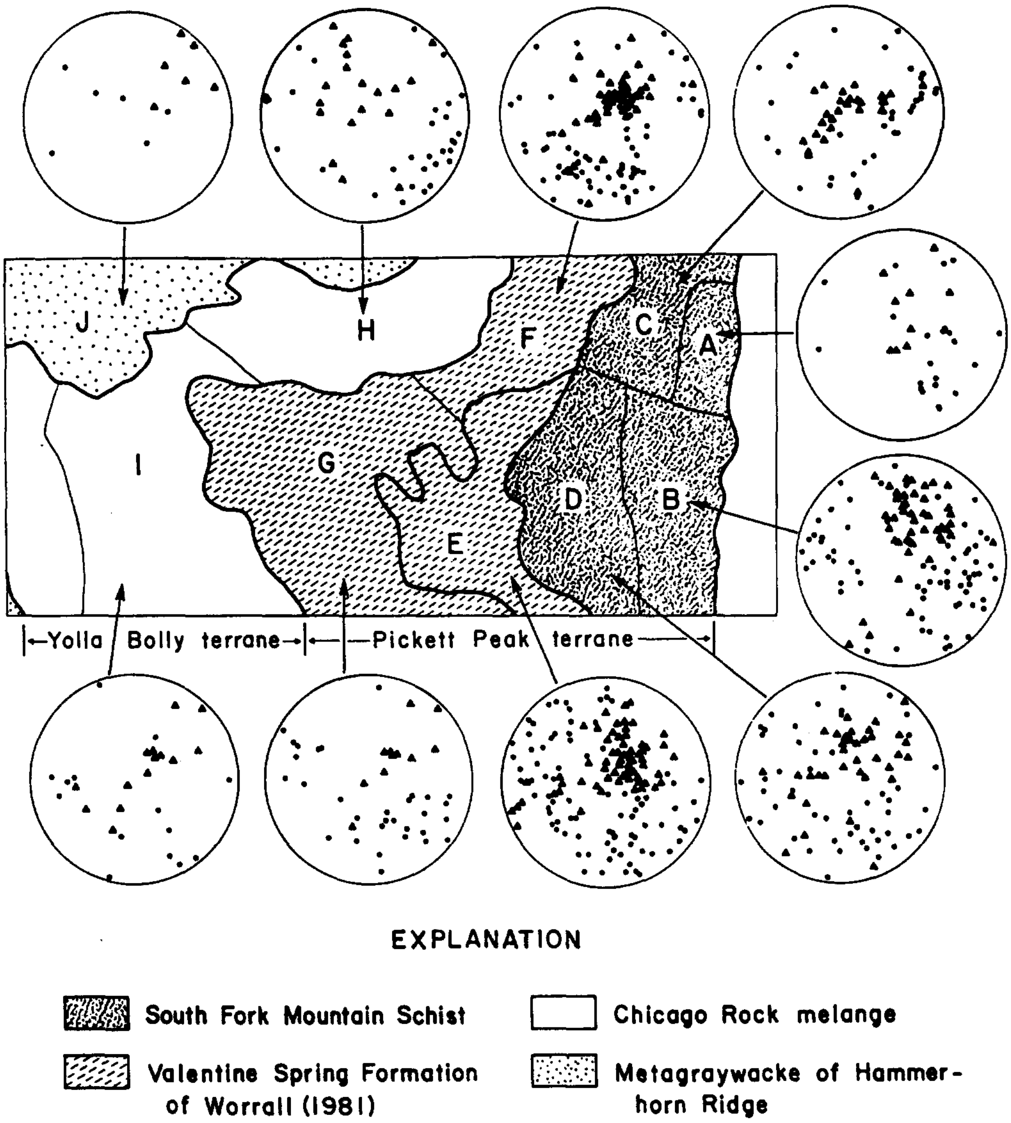


Fig. 6. Map showing distribution of structural subareas and corresponding poles to F_2 axial planes (triangles), and L_2 hinges and intersection lineations (dots).

the NW and SE quadrants locally (Fig. 6). The trend of these lineations is towards the NW and SE along the strike of the axial plane except in subarea F where the plunge tends to be in the dip direction. The down-dip plunges are highly localized and may reflect local rotation of the fold hinges near the Log Springs fault as described for other thrust faults (Bell 1978, Williams 1978). In the Yolla Bolly terrane, F_2 folds are tight to isoclinal. Numerous km-scale folds are well defined by coherent radiolarian chert interbeds within the metagraywacke (see Fig. 2). On the north limb of the regional F_4 antiform, F_2 folds in Yolla Bolly metagraywacke and chert have axial planes that consistently dip gently to moderately to the northeast and are overturned to the southwest (Blake 1965).

The most conspicuous L_2 lineations are intersection lineations formed by either $S_1 \times S_2$ in the Pickett Peak terrane or $S_0 \times S_2$ in the Yolla Bolly terrane. These lineations are commonly observed in mica schist, Chinquapin metabasalt, TZ 3A or 2B metagraywacke, or slaty argillite and only rarely in greenstone and chert. In TZ 2A and TZ 1, the metagraywacke lineation is commonly not well developed, but it is most easily observed in slaty argillite interbedded with massive metagraywacke. The textural grade of most of the western part of the Yolla Bolly terrane rocks is low 2A to 1, and L_2 structures are scarce.

L_2 blue amphibole mineral lineations are observed in metacherts and metavolcanic rocks of the Pickett Peak terrane. From thin-section studies, it appears that the L_2 amphibole lineations are formed primarily by the rotation of amphiboles into the S_2 foliation and are not due to widespread crystallization of blue amphibole, although blue amphibole that crosscuts S_1 fabric is present locally.

D_3 *structures*

D_3 structures occur in both the Yolla Bolly and Pickett Peak terranes; however, the style of folding differs between the two. S_3 is a crenulation cleavage and is observed throughout the Pickett Peak terrane and less commonly in the Yolla Bolly terrane. The foliation is

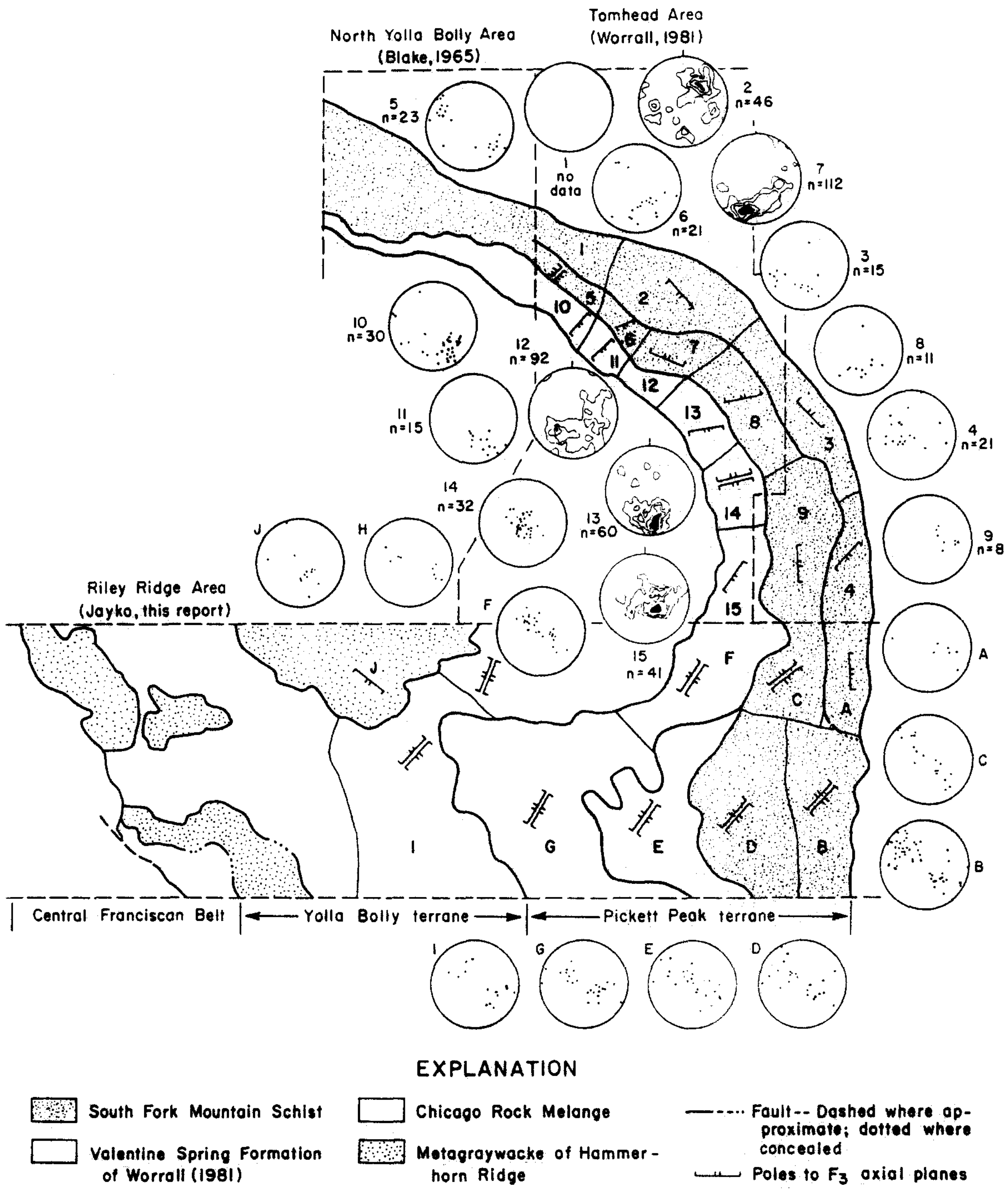


Fig. 7. Map showing distribution of structural subareas and corresponding equal-area stereonet plots of poles to F_3 axial planes from Blake (1965), Wood (1971), Worrall (1981) and this study.

typically defined by rotation of metamorphic phyllosilicates into the F_3 axial planes in both the Pickett Peak and Yolla Bolly terranes. D_3 deformation apparently occurred at shallower structural levels than D_1 and D_2 as there is no evidence for development of blueschist facies minerals associated with D_3 fabric.

Map-scale F_3 folds are observed throughout the study area. They are well defined by the chert horizons in the Hammerhorn Ridge unit, and moderately well defined by tuffs in the South Fork Mountain Schist. In the Pickett Peak terrane, the folds are commonly asymmetric and close to tight, whereas in the Yolla Bolly terrane they are often kink-like and more rarely, box and conjugate (Figs. 4e & f). In the Riley Ridge area, the poles to axial planes of both terranes tends to fall into two concentrations, this combined with the common occurrence of box folds suggests conjugate folding with moderately dipping, NE-striking axial planes (Fig. 7). Hinges are generally subparallel to the strikes of axial planes, with shallow NE–SW plunges (Fig. 8). The overall geometry of the F_3 folds in much of the area indicates layer-parallel shortening (Ramsay 1962) suggesting that the folds were most likely induced tectonically rather than by gravity. The orientation of the F_3 fold axis and axial planes suggests that the principal compression direction was oriented approxi-

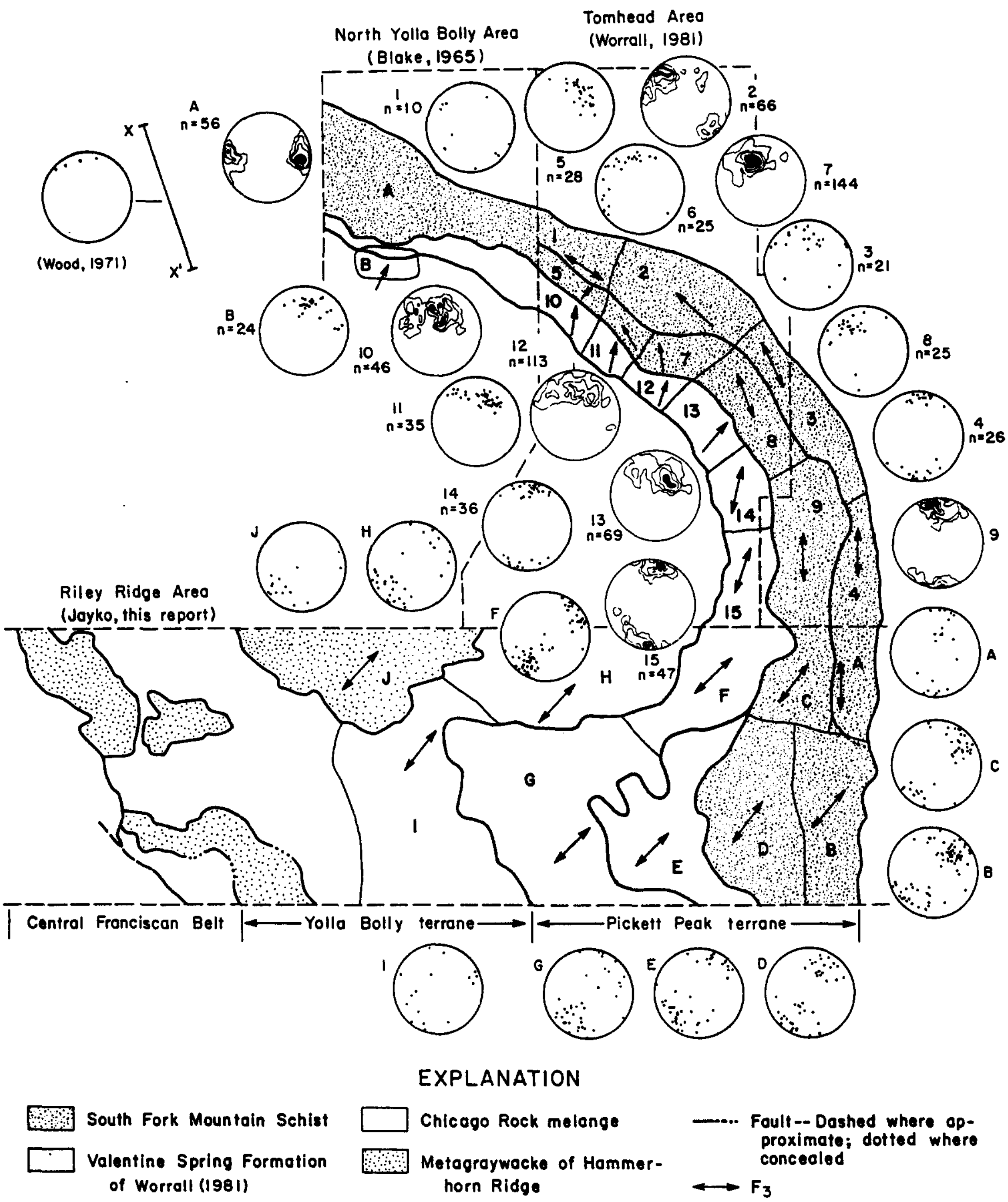


Fig. 8. Map showing distribution of structural subareas and corresponding equal-area stereonet plots of F_3 hinges and intersection lineations.

mately subhorizontal and NW–SE, normal to the D_1 and D_2 movement directions.

F_2 and F_3 axial planes projected onto cross-sections approximately normal to the dips (Fig. 9) show that the moderate-to-steep, SW-dipping F_2 axial planes seem to be slightly steeper toward the SE than to the north, and that the variably dipping F_3 axial planes contrast with the generally consistent orientation of F_2 axial planes.

D_4 *structures*

The large-scale folds that warp the Eastern Franciscan belt thrust sheets are defined on a regional basis (Fig. 2) (Suppe 1973, Worrall 1981, Blake & Jayko 1983). The SE-trending Yolla Bolly antiform (Worrall 1981) is about 7–10 km wide and well defined by the folded Hammerhorn Ridge unit. The textural zones are folded on a regional scale, with the lowest grade rocks in the core of the antiform indicating that the folding postdates D_2. On the north limb of the regional F_4 antiform, F_2 axial planes dip NE (Blake 1965) suggesting that they are folded. A large synform to the southwest of the antiform is also suggested by the map pattern but not well constrained by attitudes, due to complications resulting from earlier folding and refolding of Yolla Bolly rocks. The axial trace may run through Chicago

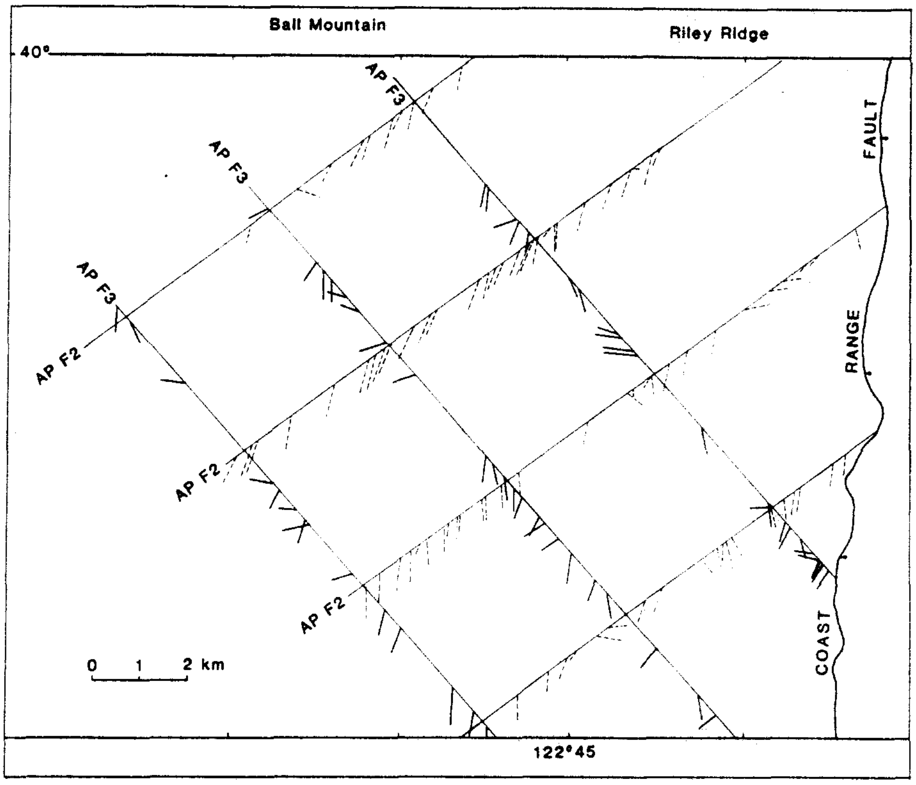


Fig. 9. F_2 and F_3 axial planes from the eastern half of transect projected onto sections approximately normal to the dip directions of axial planes. Dotted lines indicate dip of F_2 axial planes, solid lines indicate dip of F_3 axial planes.

Rock melange between the westernmost and central exposures of Hammerhorn Ridge unit within the Riley Ridge area. Linear topographic features and alignment of benches suggest that the western margin of the Hammerhorn Ridge unit at Smokehouse Ridge may be modified by a high-angle normal fault, east-side-up, thus modifying the synformal axis.

Regional analysis of structural data

Stereonet plots of poles to S_1, F_3 axial planes and F_3 axes compiled from Blake (1965), Wood (1971), Worrall (1981) and this study (Figs. 5, 7 and 8) demonstrate the arcuate trend of early foliation due to the late regional antiform. The inside set of poles to foliation from the Valentine Spring Formation and the Yolla Bolly terranes best define the large 'Yolla Bolly' antiform of Worrall (1981) (stereonet plots B, 10, 11, 12, 13, 14, F, G and H, Fig. 5). The outer sets of poles also shows a less well defined progressive rotation of foliation within the South Fork Mountain Schist (area A, 1–9, a–d, Fig. 5). The complimentary synform to the SW is not well defined by structural attitudes. Area J on the NE limb of the inferred synform is dominated by N-dipping foliation, although large scatter is evident.

Regional data are not available for F_2 folds. The orientation of F_3 structures in the upper part of the South Fork Mountain Schist are more N- to NW-trending than those of the structurally lower Valentine Spring Formation and the South Fork Mountain Schist of areas B, C and D of this study (Figs. 7 and 8). F_3 structures were reoriented from NE-trending to NW-trending above the Tomhead fault (Worrall 1981) and the northern segment of the Ball Mountain fault after the main pulse of D_3 deformation.

The hinge lines and L_3 intersection lineations show a progressive variation in plunge from predominantly NE or NW in the north, to predominantly SW in the south. F_3 axial plane orientations are more erratic. The bimodal distribution of poles that is common in the Riley Ridge area is absent in the north. The loss of the conjugate F_3 axial planes northward may be due to a greater amount of shortening (plus 45% ?, Paterson & Weiss 1966), creating tighter, overturned folds rather than box folds.

Figure 2 shows a generalization of the Eastern Franciscan belt geology with the schematic location of the F_2, F_3 and F_4 structures. The F_4 Yolla Bolly antiform and corresponding synform fold and warp both the Pickett Peak and Yolla Bolly terranes. These large folds appear to be truncated to the east by the Coast Range fault and probably to the north by the South Fork fault. Figure 10 shows the schematic development of D_1–D_4 structural elements.

Faults

With the exception of the Coast Range fault, actual fault surfaces corresponding to the major tectonic breaks described in this paper are difficult to find in outcrop due to poor exposures and similarities between rocks within the upper and lower plates. However, the contacts between units can usually be located within a few meters or tens of meters. The dip direction of the faults is inferred from the topographic expression of the contact.

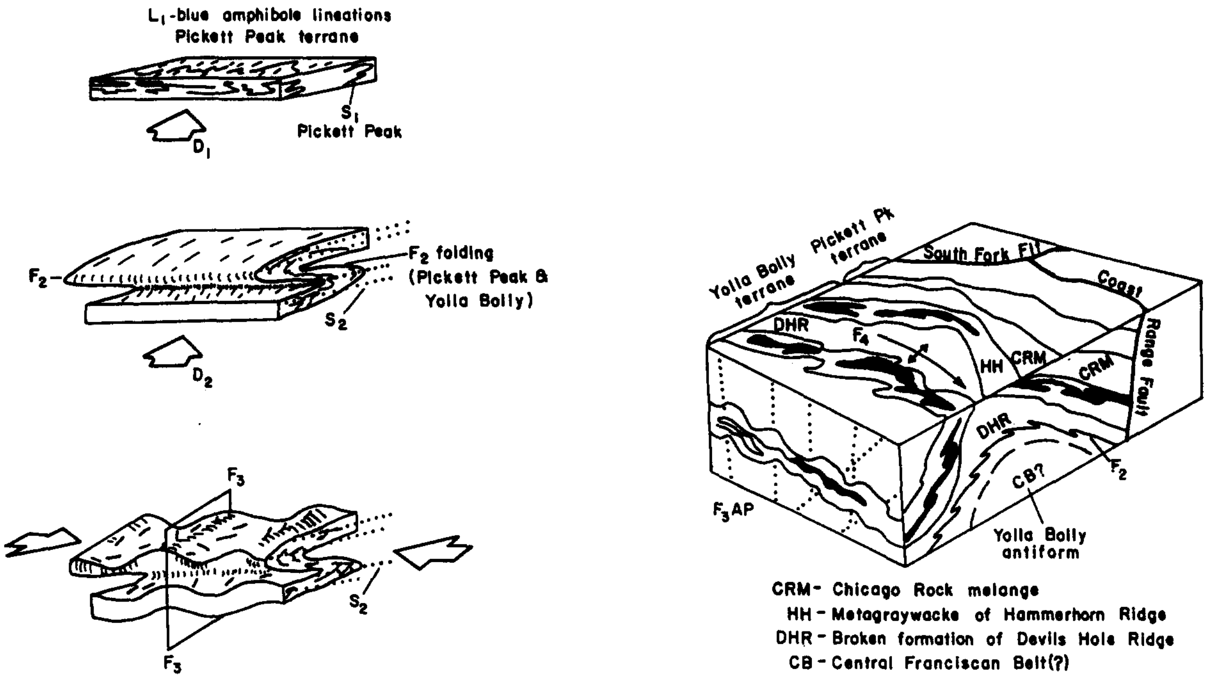


Fig. 10. Block diagram showing generalized orientation of F_2, F_3 and F_4 trends in the Eastern belt of the Franciscan Complex.

In most cases, rocks of either higher metamorphic grade, or older age, presently occur structurally above lower grade, younger rocks suggesting that the faults are thrusts. See Fig. 2 for location of the major faults.

Coast Range fault. The contact between the Pickett Peak terrane and Coast Range ophiolite was originally interpreted as a major Mesozoic thrust fault, the Coast Range thrust, and was thought to represent a paleo-subduction zone (Bailey *et al.* 1970, Ernst 1970). Recent work indicates that the Coast Range thrust along the west side of the Sacramento Valley is a late Cenozoic, high-angle fault that is more appropriately called the Coast Range fault (Worrall 1979, Hopson *et al.* 1981, Griscom 1983, Jayko 1984, Blake *et al.* 1985, Jayko & Blake 1986). In one excavated exposure the Coast Range fault was measured as striking 007° and dipping 67° east.

Tomhead fault. The Tomhead fault (Worrall 1981) lies within the South Fork Mountain Schist. Worrall (1981) defined the contact based on differences in the metavolcanic rock and fabric above and below the fault. Within the Riley Ridge study area, this fault is inferred to bound structural subareas A and C, as F_3 structural elements were slightly discordant in this area similar to Worrall's (1981) areas to the north (Figs. 7 and 8); however, the fault was not observed in the field.

Ball Mountain fault. The contact between the South Fork Mountain Schist and the Valentine Spring Formation is defined by a pronounced difference in lithology; crenulated mica schist vs schistose-to-gneissic metagraywacke. The contact mapped by Worrall (1981), is correlated with the Log Springs fault of Suppe (1973). Recent mapping to the south of the Riley Ridge study area suggests that the Log Springs fault at Log Springs separates TZ2B and TZ3A metagraywacke of the Valentine Spring Formation. We suggest retaining the name Log Spring fault for the TZ 2B–TZ 3A contact within the Valentine Spring Formation as expressed at Log Springs. The fault that separates the Valentine Spring TZ 3A metagraywacke and the South Fork Mountain Schist we refer to as the Ball Mountain fault, after a prominent peak that the fault crosses in the Ball Mountain quadrangle.

Log Springs fault. The Log Springs fault, as redefined above, separates TZ 3A and TZ 2B metagraywacke within the Valentine Spring Formation at Log Springs and north into the Riley Ridge area. A pronounced change in fabric orientation, as well as a change in textural grade along the northern extent of the contact, suggests a fault boundary rather than a gradual transition. Toward the southwest, the pronounced break in fabric is not apparent, and the contact appears to be folded as suggested by prominent embayments.

Sulphur Creek fault. The boundary between the Chicago Rock melange and Valentine Spring Formation is defined by the first appearance of numerous blocks of greenstone, chert, and minor serpentinite that characterize the Chicago Rock melange. This boundary approximately coincides with the TZ 2A–2B isotect. The contact is interpreted as a thrust fault. This fault was first mapped in the Yolla Bolly 15 minute quadrangle by Worrall (1981) and named the Sulphur Creek fault. The contact appears to be gently E-dipping along its southern extent but becomes considerably steeper (up to 70°) to the north.

A pronounced difference in the orientation of the foliation across the Sulphur Creek fault was first observed by Worrall (1981) and is also observed in the northern part of the study area. This fabric contrast becomes less pronounced toward the southwest. The Sulphur Creek fault is interpreted as a major fault zone separating the Yolla Bolly and Pickett Peak terranes (Blake & Jayko 1983).

Chicago Camp fault. The Chicago Rock melange is thrust over the Hammerhorn Ridge unit along the Chicago Camp fault (Blake & Jayko 1983). Small pods of serpentinite and rare amphibolite blocks occur locally along the contact. Movements along this fault predates D_2–D_4 folds.

Red Mountain fault. The Yolla Bolly terrane is faulted against the Central Franciscan belt along an E-dipping fault, the Red Mountain fault (Blake & Jayko 1983). This contact is readily mapped from aerial photographs because of the marked contrast in topography and vegetation between the two terranes. The fault contours along several irregularly shaped prominent ridges, suggesting that locally it is fairly flat-lying. Southwest of Leech Lake Mountain, the Red Mountain fault appears truncated by a series of high-angle, probably strike-slip faults that appear to offset blocks of the Yolla Bolly terrane. The northward continuation of these faults defines a broad zone of shearing that is visible on high-altitude photographs and appears to be contiguous with the Grogan fault zone (Cashman *et al.* 1986).

Both the Pickett Peak and Yolla Bolly terranes have experienced a long history of fault activity. We show only the major unit-bounding faults at this scale. Subsidiary faulting is widespread but difficult to trace in the homogeneous mica schist, metagraywacke and argillite that dominate the terranes. The Chicago Camp and Log Springs fault appear to be the oldest faults as they are locally deformed subparallel to F_2 axial trends. The Chicago Camp fault may be one of several early imbricate thrusts that formed during initial subduction of the Yolla Bolly terrane. Activity on the Sulphur Creek fault postdates D_2 deformation associated with accretion of the Yolla Bolly terrane, so does not represent the original accretionary fault. The Ball Mountain and Tomhead faults show evidence of some of the youngest faulting within the terranes as they appear to postdate D_3 activity, at least along their northern segments.

DISCUSSION

The Eastern Franciscan belt metamorphic rocks are inferred to have been deformed and metamorphosed in a subduction zone. The Pickett Peak and Yolla Bolly terranes of the Eastern Franciscan belt are quite distinct lithologically and record slightly different deformational histories. The Pickett Peak terrane has yet to yield paleontologic data that indicates a protolith age. The Pickett Peak terrane is interpreted as a fragment of oceanic or ocean island-type crust that was overlapped by continentally derived sediments near a convergent margin and subsequently subducted. We infer that the D_1 structures formed concurrent with accretion, or underplating, of the terrane to the continental margin.

The Yolla Bolly terrane yields principally late Jurassic and early Cretaceous megafossils and radiolarians. We infer that the metamorphic age of the Yolla Bolly terrane (90–115 Ma) reflects a minimum time for the occurrence of the D_2 event, and similarly, subduction and accretion of the terrane. The Pickett Peak terrane may have been thrust to shallower levels of the subduction complex coincident with this event.

D_1 and D_2 structures probably formed in conjunction with accretion of the Pickett Peak and Yolla Bolly terranes to the continental margin in a subduction zone. The F_2 folds in both the Pickett Peak and Yolla Bolly terranes generally trend NW–SE. The axial planes have a variable dip on a regional scale due to later deformation but are generally consistently oriented within large, map-scale domains. L_1 mineral lineations and F_2 folds formed at depth during blueschist-facies metamorphism (Jayko *et al.* 1986) and, by inference, within a subduction zone.

F_3 folds may be related to emplacement of the terranes to higher structural levels. The conjugate nature of the F_3 folds suggests NW–SE directed compression. The F_4 folds trend approximately NW–SE and are the youngest structures present in the Eastern Franciscan belt. They are truncated by the younger bounding faults including the Coast Range fault and high-angle faults along the western margin of the Yolla Bolly terrane.

There is a pronounced contrast in metamorphic facies between the Eastern Franciscan belt and rocks which lie to the east in the Klamath Mountains and the eastern part of the Coast Ranges. The South Fork Mountain Schist is juxtaposed against prehnite–pumpellyite-facies rocks of the Galice Formation in the Klamath Mountains (Irwin *et al.* 1974, Harper & Wright 1984), and against the Coast Range ophiolite, which is overprinted by low-grade, ocean floor metamorphism in the Coast Ranges (Hopson *et al.* 1981). Assuming that the blueschist-facies rocks are not entirely exotic and accreted to the margin as a metamorphic block then juxtaposition of the blueschist-facies rock from depth must have been accompanied by considerable omission of structural section suggesting a component of normal faulting.

The Pickett Peak and Yolla Bolly terranes of the Eastern Franciscan belt record deformation and metamorphism associated with successive accretion events during early and mid-Cretaceous time presumably coincident with convergence along the North American continental margin. Generally NE convergence of the Farallon plate is suggested from plate motion models for mid-Cretaceous time (115–90 Ma) (Engebretson *et al.* 1985). This inferred convergence direction is oblique to the continental margin trend as suggested by the trend of the Cretaceous batholiths (Kistler *et al.* 1971) (Fig. 11) and not inconsistent with the orientation of fabric elements within the Eastern Franciscan belt.

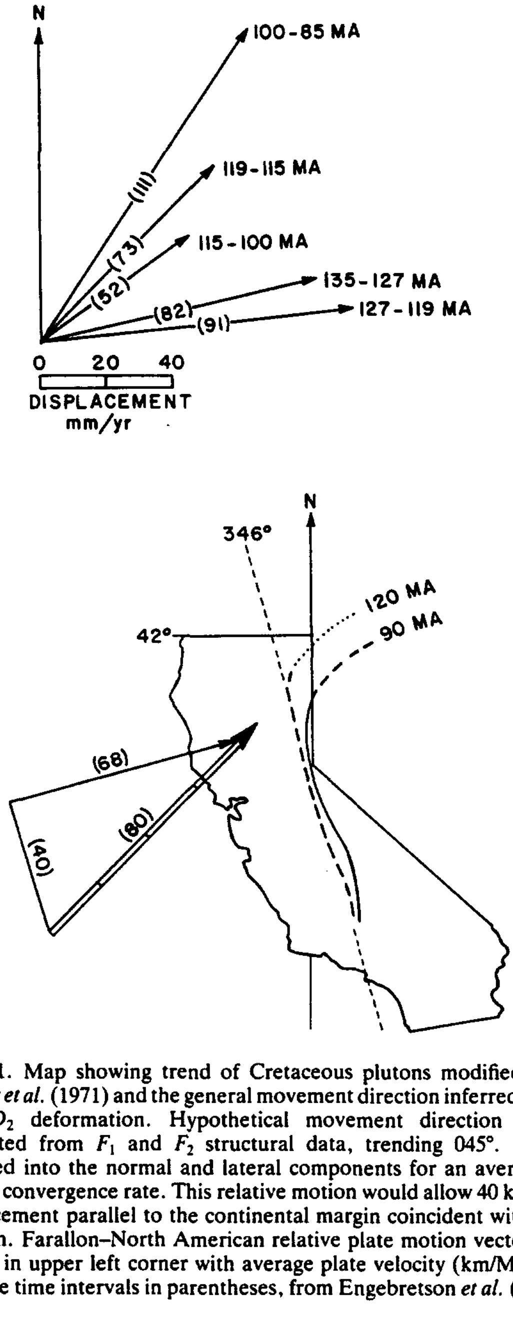


Fig. 11. Map showing trend of Cretaceous plutons modified from Kistler *et al.* (1971) and the general movement direction inferred for D_1 and D_2 deformation. Hypothetical movement direction vector suggested from F_1 and F_2 structural data, trending 045°. Vector resolved into the normal and lateral components for an average 80 mm/yr convergence rate. This relative motion would allow 40 km/MA displacement parallel to the continental margin coincident with subduction. Farallon–North American relative plate motion vectors are shown in upper left corner with average plate velocity (km/MA) for discrete time intervals in parentheses, from Engebretson *et al.* (1985).

The D_1 and D_2 structures most likely formed while the rocks were subducting and underplating, whereas D_3, D_4 and most of the faults postdate subduction. The older-over-younger, and deeper-over-shallower relations between the hangingwall and footwall of most major faults suggest a major component of shortening and thrusting across faults within the Eastern Franciscan belt terranes.

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