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Tectonic Correlations, Klamath Mountains and Western Sierra Nevada, California

Abstract: The Klamath Mountains province of northwestern California has long been regarded by geologists as a probable northern continuation of the Sierra Nevada province. Attempts at stratigraphic correlations between the two provinces date back to the turn of the century, but attempts at correlation of tectonic elements have been hindered by a lack of data. Clark (1960) proposed a general correlation of north-striking faults in the Klamath Mountains and in the western Sierra Nevada. High-angle faults of the latter area constitute the Foothills fault system, which Clark believed to be of probable strike-slip origin. Recent studies in the southeastern Klamath Mountains demonstrate that the major faults of that region are thrust faults along which thrust plates have moved relatively westward. The contrast in geometry between subhorizontal to moderately dipping Klamath faults and steeply dipping faults of the Foothills system does not refute correlation of the two but can be explained by an eastward steepening of the Klamath thrusts into faults continuous with those of the western Sierra Nevada.

Geologic relationships indicate that the Melones fault of the Foothills fault system extends northward into the eastern Klamath region as the Trinity thrust fault. Correlation of the two faults appears probable on the basis of (1) stratigraphic and structural similarities in their hanging wall blocks, (2) the presence of thick bodies of serpentinized peridotites below the Trinity thrust plate and below the hanging wall of the Melones fault in the northwestern Sierra Nevada, (3) permissive evidence for a Late Jurassic age of the two faults, and (4) a postulated curvilinear trace for the Trinity-Melones fault which is parallel to observed curvilinear structural trends farther west. It is believed that steep minor structures within fault zones of the Foothills system, cited by others as evidence for strike-slip faulting, are not incompatible with an origin for the system by thrust faulting. Three of the four fault-bounded Klamath subprovinces are interpreted as having stratigraphic and structural counterparts in the northwestern Sierra Nevada. The Klamath central metamorphic subprovince is regarded as a thrust slice of Devonian(?) metamorphic rocks, which thins northward and southward and is not present in the Sierran region.

Eastward steepening of the proposed Klamath-Sierran thrust faults is related to their increasing proximity to the Sierran synclinorium and to their rooting into its western flank. Formation of the thrusts occurred in the Jurassic during a lengthy interval of profound crustal downbuckling and shortening. Rooting of the thrusts into a crustal zone undergoing contemporaneous subsidence and shortening rules out an origin for them by gravitational tectonics from an orogenic high or by extrusion tectonics from a dilating zone. The geometry of Mesozoic orogenesis in the Klamath-Sierran region, including thrust faulting, can best be explained by the convergence of subcrustal convection cells along the axial zone of the Sierran synclinorium.

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INTRODUCTION

The Klamath Mountains geological province of northwestern California and southwestern Oregon has long been regarded by geologists as a probable northern continuation of the Sierra Nevada province, despite the separation of the two pre-latest Jurassic terranes for approximately 60 miles by Cretaceous and younger rocks of the northern Great Valley and southern Cascade Range provinces. Hershey (1901, p. 245), for example, regarded the Klamath region as "merely a sort of outlier of the Sierra Nevada, so far as its stratigraphical and earlier dynamical geology is concerned," and Irwin (1966, p. 28) has recently written that the "lithic and structural trends of the southern Klamath Mountains correspond to those of the northern Sierra Nevada." Attempts at correlation of stratigraphic units in the Klamath and Sierran provinces date back at least to the turn of the century, but attempts at correlation of particular structural elements in the two regions have not yet been made.

A regional survey of Klamath structure was not available until 1960, when Irwin presented a geological reconnaissance of the Californian portion of the province. Using Irwin's Klamath data, Clark (1960, p. 487 and his Fig. 1) suggested general correlation of the high-angle Foothills fault system in the western Sierra Nevada with faults in the Klamath Mountains—at a time when the geometry of the Klamath faults was little known. Subsequent structural studies in those portions of the Klamath province nearest the Sierra Nevada have established the presence of major low-angle thrust faults along which thrust plates have moved relatively westward (Irwin and Lipman, 1962; Irwin, 1964; Davis and others, 1965; Davis, 1964, 1968). The contrast in geometry between subhorizontal to moderately dipping Klamath faults and steeply dipping faults of the Foothills system does not refute correlation of the two, but can be explained by an eastward steepening of the Klamath thrusts into faults continuous with those of the western Sierra Nevada. This idea has been partially anticipated by Taliaferro (1942, p. 110) who considered the steep faults of the Foothills system to be thrusts (with westward movements) which, prior to erosion, "probably decreased in angle upward and formed relatively low-angled thrust sheets."

This paper is an amplification of the idea expressed in Davis (1968, p. 929) and in Burchfiel and Davis (1968, p. 176) that Klamath thrust faults may be represented in the western Sierra Nevada by faults of the Foothills system. Specific topics of the paper are: (1) correlation of the Trinity thrust fault of the Klamath Mountains with the Melones fault of the western Sierra Nevada; (2) the direction and sense of slip along the Melones fault; (3) correlation of Klamath and western Sierran fault-bounded terranes; and (4) the implications of suggested correlations of Klamath and Sierran structures on the nature of Mesozoic orogenesis in this part of the Cordillera.

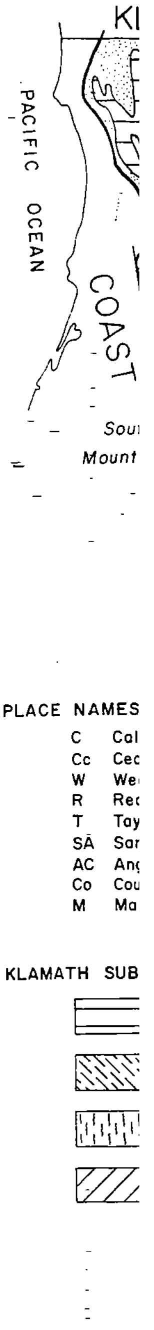
ACKNOWLEDGMENTS

Conversations with B. C. Burchfiel have contributed significantly to the ideas expressed in this paper. The writer wishes to thank Mason L. Hill, Robert H. Osborne, and Ben M. Page for suggesting improvements in the manuscript. Past financial support from the National Science Foundation (Research Grant NSF-GP-1132) has been an important factor in the writer's understanding of Klamath geology. Funds for manuscript preparation have been made available by the University of Southern California through an NDEA research and publication grant.

CORRELATION OF TRINITY AND MELONES FAULTS

Geologic relationships discussed below indicate that the Melones fault, the most prominent member of the Foothills fault system, extends northward from the northern Sierra Nevada (as mapped by Clark, 1960, his Pl. 1; Burnett and Jennings, 1962; McMath, 1966, his Fig. 1) into the eastern portion of the Klamath province as the Trinity thrust fault (Davis, 1968, p. 923–927, his Fig. 1). If so, the two faults are portions of a major crustal break at least 350 miles in length, which extends from near the Oregon border southward to near Mariposa in the western Sierra Nevada (Fig. 1). The northern end of the inferred Trinity-Melones fault is covered by Cretaceous and younger rocks; the southern end is truncated by a granitic intrusive body which is part of the Sierra Nevada batholith.

Both the Trinity and Melones faults occupy an eastern position in their respective terranes. Both faults bound on the west a thick hanging-wall sequence of eugeosynclinal Paleozoic and Mesozoic rocks which becomes progressively younger eastward (Fig. 2). In the Klamath



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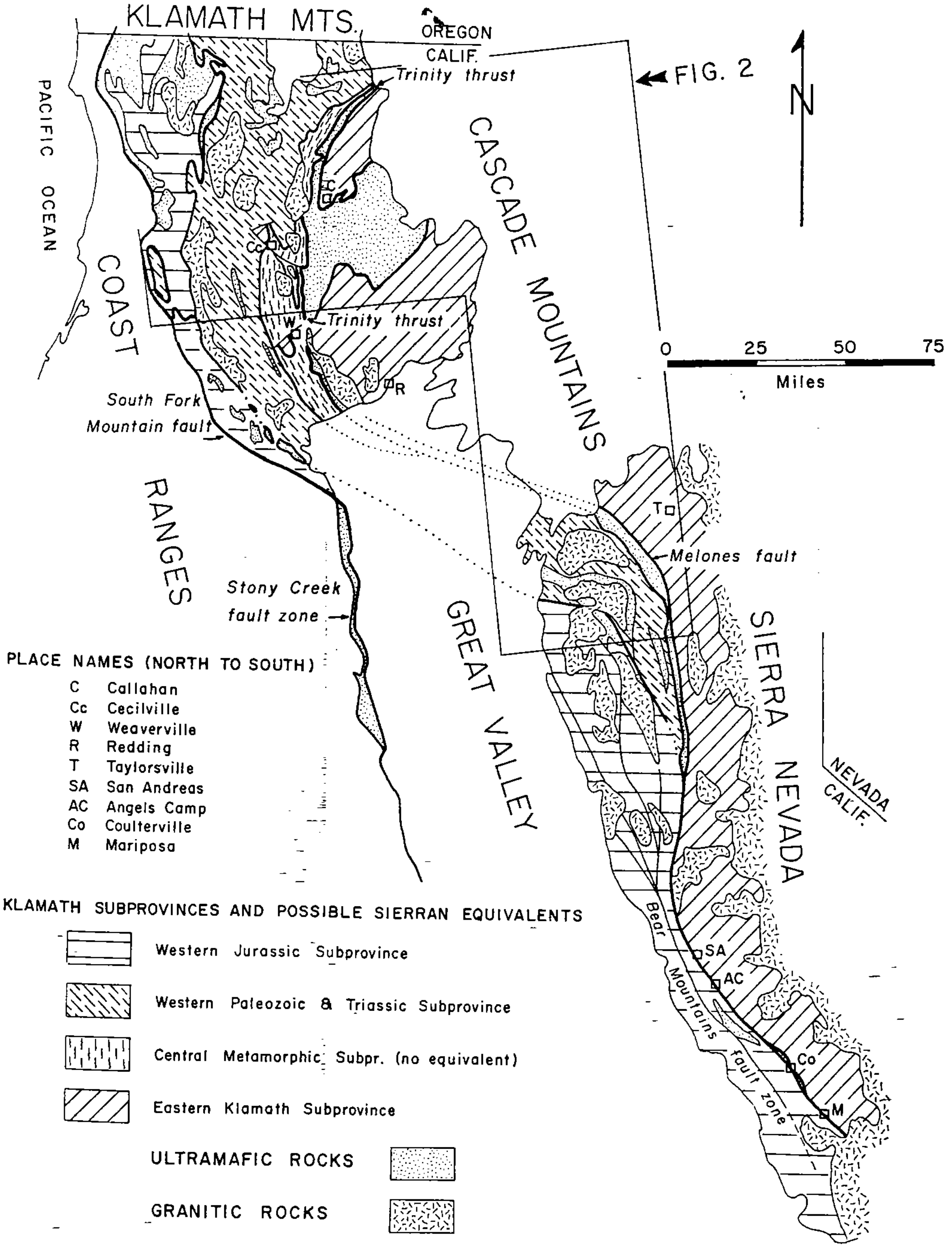

Figure 1. Generalized geologic map of Klamath Mountains and western Sierra Nevada, California, showing inferred correlation of fault-bounded terranes in the two provinces (base map: Geologic Map of California, U.S. Geol. Survey Misc. Geol. Inv. Map I-512, 1:2,500,000, 1966).

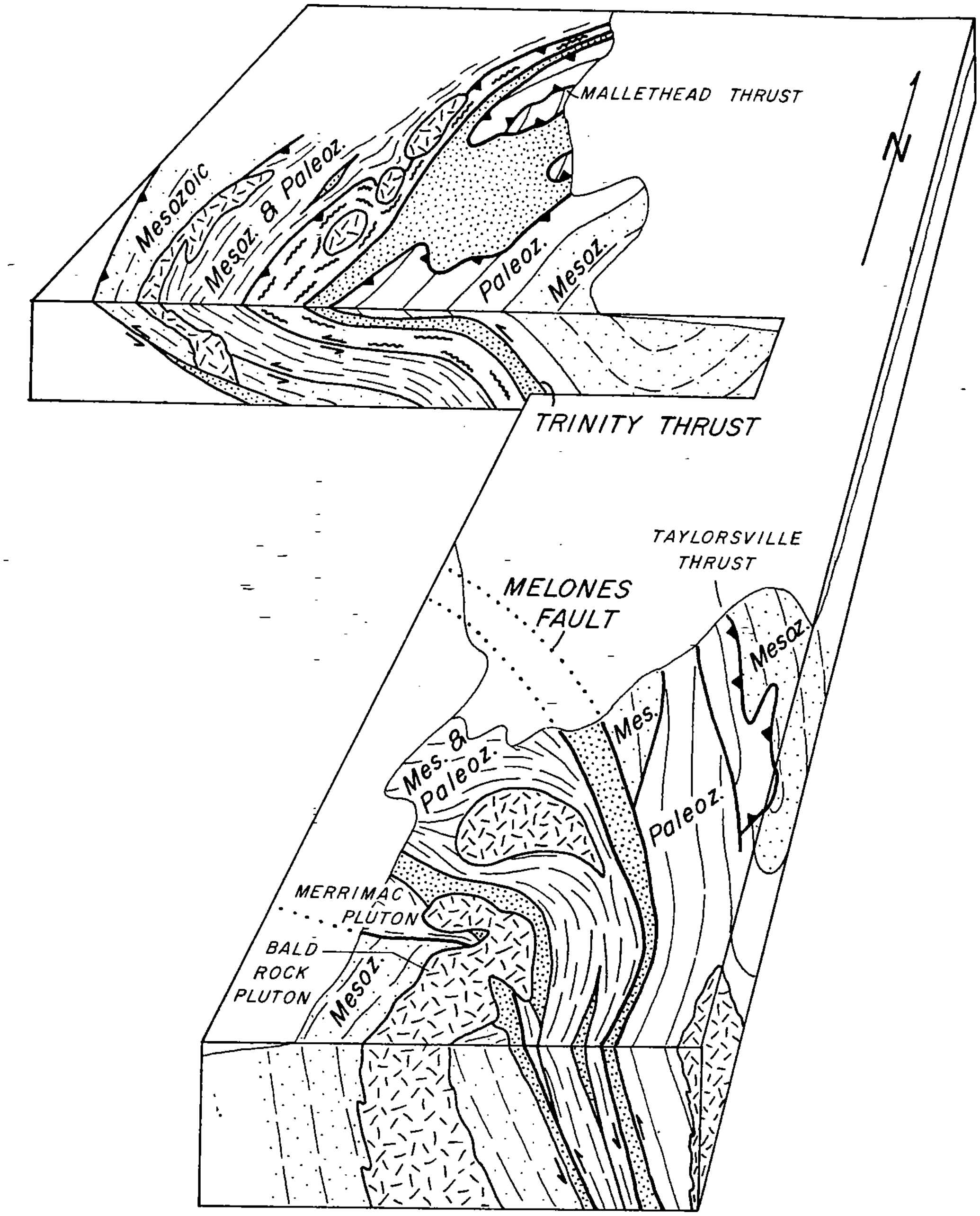

Figure 2. Schematic block diagram of a portion of Figure 1, showing inferred structural relationships across the Trinity and Melones faults (base map same as for Figure 1, with modifications *from* McMath, 1966, Fig. 1).

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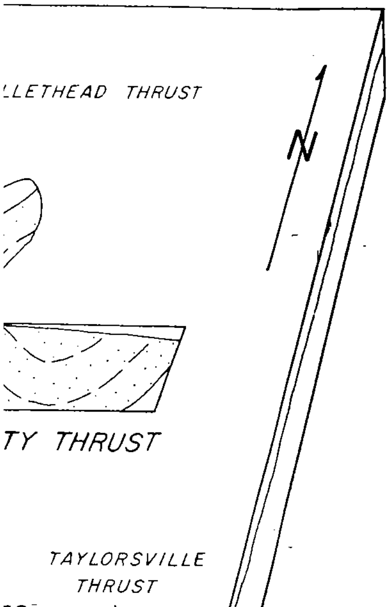

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Mountains, this sequence has been designated the eastern Klamath belt (Irwin, 1966, p. 21–23) or subprovince and includes rocks representing all periods from the Ordovician(?) through the Jurassic. Silurian, Devonian(?), Mississippian, Permian, Triassic, and Jurassic rocks have been identified east of the Melones fault in the Taylorsville area (Fig. 1), the northernmost portion of the western Sierra Nevada (McMath, 1966, p. 174). Accurate correlation of isolated, broadly contemporaneous eugeosynclinal sections is difficult, due to facies changes and lack of fossils. Dott (1961, p. 578), however, has commented that Triassic and Permian deposits at Taylorsville appear to him to be "lithologically very much like those at Lake Shasta" in the eastern Klamath subprovince, and McMath (1966, p. 181) cites several possible correlations of Triassic units in the two areas. Lithologic similarities also exist between andesitic volcanoclastic strata of Early and Middle Jurassic age in areas east of Shasta Lake and near Taylorsville (*compare* Dickinson, 1962, p. 1246).

The hanging-wall sequences east of the Melones and Trinity faults share structural as well as stratigraphic similarities. Stratified rocks east of the Melones fault zone comprise the western limb of a major synclinorium (Bateman and Wahrhaftig, 1966, p. 115, 122–125; Clark, 1964; Bateman and Eaton, 1967, p. 1408). This limb is locally overturned to the northeast in the Taylorsville area (McMath, 1966, p. 174–175), and is almost certainly represented in the Klamath Mountains northeast of Redding by the east-dipping homoclinal sequence of the eastern Klamath subprovince. The inferred position of the axis of the Sierran syclinorium in the Klamath region—just east of the easternmost exposures of the province (Fig. 2)—is directly along the northward trend of its projection from the northern Sierra Nevada through the Taylorsville area (McMath, 1966, p. 174). Although eastward low-angle faulting is not common in the eugeosynclinal half of the Cordilleran orogen (Burchfiel and Davis, 1968), it is represented in the Taylorsville area by the Taylorsville thrust (McMath, 1966) and possibly near Callahan in the eastern Klamath subprovince by the Mallethead thrust (Churkin and Langenheim, 1960, p. 270–271). This tectonic similarity may not be significant since the two thrust faults appear to have different structural settings, but it is worth noting in a comparison of the two hanging-wall terranes, until more is known of their pre-latest Jurassic structural history.

The Trinity thrust plate is underlain by the Trinity ultramafic pluton, a subhorizontal peridotitic sheet with a probable areal extent prior to erosion of more than 3000 square miles (Irwin and Lipman, 1962; Lipman, 1964; Davis, 1968, p. 924–925). The sheet, which is largely serpentinized, is several thousands of feet thick in most areas where control data is available, although it locally thins out completely beneath klippen of the Trinity thrust plate near Weaverville (Irwin, 1963) and Cecilville (Davis, 1968, his Pl. 1). Serpentinized peridotitic rocks also crop out below the hanging wall of the Melones fault in the northern Sierra Nevada, although their correlation with rocks of the Trinity ultramafic pluton, as inferable from Figures 1 and 2, cannot be demonstrated at this time. The steeply dipping Melones ultramafic body has an outcrop width west of Taylorsville of up to three miles, and a probable continuity south along the Melones fault of 100 miles (Lydon and others, 1960; Burnett and Jennings, 1962; Strand and Koenig, 1965). Still farther to the south along most of the remaining length of the Melones fault, Paleozoic rocks of the hanging wall are juxtaposed directly against Mesozoic rocks of the footwall, although large ultramafic bodies do occur within the fault zone north and south of Coulterville (Clark, 1964, his Pl. 1).

The age and structural relationships of the Trinity ultramafic pluton to the Trinity thrust fault have not been completely resolved. Davis (1968, p. 924–927) suggested that the two most likely relationships are either (1) that the pluton was intruded along the Trinity thrust during or after thrust faulting of probable Jurassic age, or (2) that the pluton was intruded into rocks of the central metamorphic subprovince during Paleozoic regional metamorphism, and that rocks of the eastern Klamath subprovince were later thrust across it. Strong support has been given to the second alternative by newly published radiometric dates on hornblendes from gabbroic rocks associated with the Trinity ultramafic pluton. K-Ar ages determined from three gabbroic samples range in age from 333 ± 16 to 439 ± 18 m.y. (Lanphere and others, 1968, p. 1043) and bracket the 380 m.y. age of regional metamorphism of the central metamorphic subprovince, as determined by the same investigators (Lanphere and others, p. 1033–

1034; Rb-Sr technique.) Although the gabbroic rocks are interpreted by Lanphere and others as being syntectonic with the Trinity pluton, this relationship has not yet been documented. The validity of the hornblende isotopic ages is also open to question; the hornblendes are derived from pyroxenes and the possibility of the ages being affected by excess radiogenic argon has been raised, but discounted, by Lanphere and others (1968, p. 1047). In light of these uncertainties and others (*see* Davis, 1968, p. 924–927), it is premature to accept either of the two alternatives for emplacement of the Trinity pluton cited above as conclusive, although present evidence clearly favors the second. This interpretation is shown in Figure 2 by the placing of thrust barbs along the upper contact of the Trinity pluton. The possibility that some ultramafic rocks in the western Sierra Nevada are of Paleozoic age has been raised by Putman and Alfors (1965, p. 362).

Available information is permissive in support of a synchronous Late Jurassic age for the inception of the Melones and Trinity faults and for displacements along them. Clark (1960, p. 494–495) considers the Foothills fault system to be of Late Jurassic age. Rocks as young as late Oxfordian or early Kimmeridgian are cut by the Melones fault, which is presumed by Clark to be of about the same age as other faults in the system. Faults in both the western Sierra Nevada and the southeastern Klamath Mountains are truncated by isolated dioritic and quartz dioritic plutons of Late Jurassic age, on the basis of geologic and radiometric data (Clark, 1960, p. 494; Irwin, 1966, p. 28; Davis, 1966, p. 47–48).

Rocks of the Trinity thrust plate are overlapped unconformably by the Great Valley sedimentary sequence, which includes elsewhere rocks as old as latest Jurassic (Tithonian; Irwin, 1966, p. 29). The youngest rocks exposed at the base of the thrust plate are in the Bragdon Formation of Mississippian age, thus establishing a lower limit to the time of formation of the plate. The overlying stratigraphic sequence contains rocks of Mississippian to Jurassic age and terminates with the Middle Jurassic (Bajocian) Potem Formation (Sanborn, 1960). This sequence contains several unconformities, but none have been described as being characterized by angular discordance. Thrusting of the Trinity plate is thus most reasonably assigned to the Late Jurassic Nevadan orogeny as represented by the regional angular unconformity at the top of the eastern Klamath sequence.

However, the possibility of earlier thrusting has been raised by Lanphere and others (1968, p. 1038) because of probable Permian ages for two small granitic plutons in the eastern Klamath Mountains. One, the Castle Crags pluton, appears to intrude the Trinity ultramafic sheet, whereas the second, the Pit River stock, intrudes Paleozoic rocks in the Trinity thrust plate about 10 miles north of Redding. The north-south alignment of these two plutons is parallel to other plutonic trends in the Klamath Mountains and suggests to Lanphere and others (1968, p. 1043) that the Trinity ultramafic pluton and Trinity thrust plate may have reached their present position with respect to one another prior to the time of granitic intrusion. This writer regards the north-south alignment of the two granitic plutons, which are approximately 30 miles apart, as probably coincidental, and tentatively assigns the Pit River stock to the Trinity allochthon. Structural evidence for major thrusting in the eastern Klamath region in the time interval between Mississippian deposition of the Bragdon Formation and Permian(?) intrusion of the Pit River stock (246 m.y., Lanphere and others, 1968, p. 1038) is not impressive. A "faunal hiatus" between the Mississippian-Early Pennsylvanian Baird Formation and the Late Pennsylvanian(?)-Early Permian McCloud Limestone appears to represent most of Pennsylvanian time (Skinner and Wilde, 1965, p. 11), but the Baird-McCloud contact is characterized by "little or no physical evidence of major unconformity." Considerable disagreement exists on the nature of this contact, which in the Shasta Lake area north of Redding is complicated by igneous intrusion and probable, pre-intrusive high-angle(?) faulting (Albers and Robertson, 1961, p. 22 and Pl. 1). Coogan (1960, p. 250) describes the Baird-McCloud contact as at least locally conformable. Thompson and others (1946, p. 21) regard it as a disconformity. Demirmen and Harbaugh (1965, p. 139) state that the oldest beds of McCloud Limestone interfinger with clastics of Baird lithology, a relationship confirmed by Skinner and Wilde (1965, p. 12). Irwin (1966, p. 31 and Fig. 6) suggests that the intruded contact in the Shasta Lake area may be a major low-angle fault. According to Albers and Robertson (1961, p. 40, 62), the Baird Formation was probably folded prior to its intrusion by the Pit River

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Thus, physical evidence for major deformation of Pennsylvanian age in the eastern Klamath region is not strong. It is also conceivable, although not probable, that thrusting of the Trinity plate might coincide with other reported or inferred breaks in Late Paleozoic sedimentation in this area. The Bragdon-Baird contact of Mississippian age may be a disconformity (Albers and Robertson, 1961, p. 18). The McCloud-Nosoni contact of Permian age is generally considered to be a disconformity (Albers and Robertson, 1961, p. 24; Thompson and others, 1946, p. 21–23), although it (as is the Baird-McCloud contact) is also complicated in the Lake Shasta area by igneous intrusion and pre-intrusive faulting. Coogan (1960, p. 251, 253) considers the McCloud-Nosoni contact to be gradational and conformable in the northern part of the East Shasta Lake area, but Skinner and Wilde (1965) regard the contact as a regional erosional unconformity. Although a Late Paleozoic age for thrusting of the easttern Klamath subprovince as implied by Lanphere and others (1968, p. 1043) cannot be discounted, it is the writer's opinion that structural and stratigraphic evidence in this region favors formation of the Trinity thrust plate during the Late Jurassic.

Connection of the Trinity and Melones faults beneath the cover of younger sedimentary and volcanic rocks now separating them requires a sharp westward bend in the buried northward extension of the Melones fault (Fig. 1). This postulated curvilinear trend is supported by (1) observable changes in trend of faults in the southern Klamath Mountains and northwestern Sierra Nevada, by (2) the absence of the Melones fault in the Klamath terrane, if it is projected rectilinearly along strike from the Taylorsville area, and by (3) the curvilinear trend of the younger zone of faulting to the west which separates the Klamath Mountain and Great Valley provinces from the northern Coast Ranges (Fig. 1). This zone, which includes the Stony Creek and South Fork Mountain faults, has also recently been interpreted as a major thrust zone (Irwin, 1964, p. C6–C7; Brown, 1964; Bailey and others, 1964, p. 163–165; Blake and others, 1967). The curvilinear traces of the South Fork Mountain-Stony Creek and inferred Trinity-Melones fault zones parallel an apparent westward deflection of Cordilleran structural elements in the Klamath Mountains region.[1]

In summary, correlation of the Trinity and Melones faults appears probable on the basis of (1) stratigraphic and structural similarities in their eastern hanging wall blocks, (2) the presence of thick bodies of serpentinized peridotites below the Trinity thrust plate and below the hanging wall of the Melones fault in the northwestern Sierra Nevada, (3) permissive evidence for a Late Jurassic age of the two faults, and (4) a postulated curvilinear trace of the buried connecting link between the two fault segments as they are now exposed which is more or less parallel to observed curvilinear trends of structural elements farther west. The suggested eastward steepening of the Trinity thrust into a much steeper (70° to 90°) fault has precedent in Cordilleran geology. Misch (1966, p. 120–123, 133, 136) describes just such a geometry for the Shuksan thrust in the northern Cascades, as does Brown (1964, his Fig. 123.2, p. D12-D13) for the peridotite-intruded Stony Creek fault zone along the western side of the Sacramento Valley.

DIRECTION AND SENSE OF SLIP ALONG THE MELONES FAULT

The correlation of the Trinity and Melones faults proposed in this paper requires that the sense of net slip along the Melones fault be

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[1] This regional deflection is generally interpreted as an example of oroclinal folding (Carey, 1958, p. 191 and Fig. 56, his "Mendocino orocline;" Wise, 1963; Hamilton and Myers, 1966, p. 537–539), that is, the bending of an initially straighter orogenic belt during later deformation. The alignment of the offshore east-west Mendocino fracture zone with the changes in trend of Klamath and Sierran structural elements may enhance this interpretation. Although some bending of structural elements in this area appears reasonable, for example, steep faults in the northwestern Sierra Nevada (Fig. 1), it seems likely that some of the "oroclinal folding" may be a geometrical effect attributable to a westward shallowing in dip of thrust faults and intervening terranes in the Klamath region (Fig. 2)—as opposed to being solely the result of regional strain impressed on this portion of the Cordilleran orogen. According to this concept, the "Mendocino orocline" might represent in part a flap-like extension of flatter, higher and more westward levels of a Klamath-Sierran allochthon than are found in areas to the north and south.

compatible with regional westward displacement of the Trinity thrust plate relative to underlying rocks. This compatibility is not easily demonstrated, since the direction and sense of slip along the Melones and other faults of the Foothills system has been the subject of considerable disagreement over the past 40 years. Earlier workers, among them Knopf (1929, p. 45–46), Cloos (1932, p. 392–394), and Taliaferro (1942, p. 90, 110), considered that faults in the western Sierra Nevada had generally been characterized by dip-slip displacements, with eastern hanging walls up with respect to the western footwalls. Although recognizing apparent reverse fault displacement on the Melones and Bear Mountains faults (Fig. 1), Clark (1960, p. 492) suggested that strike-slip movements probably predominated in the Foothills fault system. This conclusion was based primarily on the occurrence within the fault zones and adjacent terranes of steeply plunging lineations and axes of minor folds. Questionable support has been given to Clark's preference for strike-slip movements by Baird (1962) in his structural analysis of the hanging wall of the Melones fault near Melones, a small settlement located five miles southeast of Angels Camp (Fig. 1).

Previous discussions of the nature of slip along the Melones fault appear to have been based on the *a priori* assumption that the zone has been steeply dipping since its inception. If, however, the fault, as discussed in the concluding section of this paper, was initially a low-angle thrust fault which has subsequently been tilted into its present steep position, then the problem of dip versus strike slip along it, as presently debated, loses its relevance. For example, hypothetical evidence for slip parallel to the N. 40° W.-strike of the steep Melones fault between Mariposa and San Andreas (Fig. 1) might have resulted from thrust movements to the northwest along a previously horizontal, gently, or moderately dipping Melones thrust fault. The writer does not regard evidence for fault movement with a large subhorizontal component in reference to *present* fault orientation as evidence unequivocally opposed to a thrust origin for the Melones fault. Thrusting with regional or local relative movement of the hanging wall to the northwest, followed by eastward steepening of the thrust zone, could produce a geometry of apparent strike-slip displacement.

Although more data is clearly needed on the direction and sense of displacement along the Melones fault zone, the writer believes that a case for westward displacement of the hanging wall with respect to the footwall—or reverse-slip displacement in terms of present fault geometry—is not without foundation. One line of evidence comes from the juxtaposition of Paleozoic and Mesozoic rocks along the southern half of the Melones fault. Here, steeply east-dipping footwall strata of Jurassic age, with tops generally to the east, are faulted against steeply east-dipping Paleozoic rocks of the hanging wall, also with tops generally to the east, for approximately 100 miles (Clark, 1960, p. 492–493). This juxtaposition requires very large displacements if slip has been parallel or subparallel to the present strike of the fault—perhaps in excess of 100 miles. No independent evidence has yet been presented to support such impressive strike-slip fault displacements in the western Sierra Nevada, nor for that matter anywhere in the Cordilleran region during Mesozoic orogenesis of pre-Cretaceous age. In contrast, the juxtaposition of older rocks above younger for many miles along a fault is a common consequence of thrust faulting, and in the Melones example, one which coincides temporally with Mesozoic thrust faulting in the adjacent Klamath province.

Clark (1960, p. 492) has based his argument in support of strike-slip movements (or from this writer's point of view, slip more or less parallel to the *present* strike of the fault) primarily on the occurrence of steeply plunging lineations and axes of minor folds within fault zones of the Foothills system and in adjacent terranes. Lineations and minor folds with low to moderate angles of plunge also occur within these areas, but they are generally attributed by Clark (1964, p. 56–57) to deformation(s) preceding development of the steeper minor structures. According to Clark (1960, p. 491), steep lineations in Foothills fault zone generally plunge to the southeast and east and are "formed most commonly by elongate fragments such as the clasts in volcanic breccia and in conglomerate. Most of these clasts are flat triaxial ellipsoids." Along the Melones fault between San Andreas and Angels Camp (Fig. 1), for example, Clark reports (1964, p. 57) widespread steep, east-plunging lineations "marked by elongated fragments of volcanic breccia and elongate blebs of chlorite in the metavolcanic rocks and by elongated pebbles and boulders in the mixed-pebble conglomerate of the Mariposa formation." Similar lineations are present in the Bear Mountains

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fault zone to the west and along other faults in the Foothills system. Clark (1964, p. 56) reports that elongate triaxial chert fragments (of cataclastic origin) have axial ratios as disparate as 1:15:200.

Steeply plunging lineations in pelitic rocks, termed "microcrenulations" in the field, have been observed by the writer at a number of localities within the Melones fault zone between San Andreas and the Tuolumne River (north of Coulterville, Fig. 1). At two localities, they parallel lineations defined by elongate clasts in conglomerates and pebbly siltstones; no cases with contrary geometry were seen. Axes of slip folds in the pelitic rocks have a diverse orientation with respect to the steep lineations, since the direction and amount of plunge of such folds is highly variable. One case of parallelism of minor fold axes, steep lineations, and pebble elongation was noted in a roadcut along State Highway 49, one-half mile south of Calaveritas Creek, near San Andreas.

"Microcrenulations" in pelitic rocks just south of the Stanislaus River and the settlement of Melones are seen in thin section to be due to a streaking out of micaceous aggregates and to the deflection of mica-defined foliation around silt-sized clastic grains. The grains have a distinct tendency to be elongate parallel to the mesoscopic lineation. Most are quartz, nearly all of which exhibit "pressure fringes" (or "pressure shadow zones") at their long ends. The "pressure fringes" contain finely recrystallized quartz and sericite and are not seen in sections cut normal to the lineation. Hills (1963, p. 129–130), Ramsay (1967, p. 181–182), and others regard these fringes or zones as forming adjacent to competent particles in the direction of maximum extension during deformation. This lineation trends southeastward, parallel to the long axes of triaxial clasts in adjacent conglomerates.

Clark believes that steep, east-plunging lineations of the types described above (and fold axes parallel to them) are "probably parallel to the *b* tectonic axis" (1960, p. 492) and, therefore, perpendicular to the direction of slip (kinematic axis *a*). This writer considers Clark's conclusion to be suspect. In his opinion the possibility exists that steep minor structures within the Melones and other Foothills fault zones have developed parallel or nearly so to a westward (now up-dip) direction of slip.[2] Fault zones of the Foothills system are characterized by extreme cataclasis and variable degrees of accompanying recrystallization (Clark, 1960, p. 489–491, Pl. 3). Steep lineations of the types present within these zones may have formed by penetrative cataclastic elongation and recrystallization of mineral grains and rock fragments parallel to the direction of fault displacement (that is, to the west and northwest). Lineations with this origin appear to be present in fault zones elsewhere; for example, in Precambrian granitic gneisses, quartzites, and pebbly quartzites within some Mesozoic thrust zones in the Clark Mountains area of southeastern California (B. C. Burchfiel and G. A. Davis, in progress). In this area, the long axes of triaxial mineral grains and pebbles within mylonitized rocks lie parallel to mineral smears, striations on slickensided surfaces, and to the direction of eastward thrusting—the latter as determined from the orientation of (1) overturned flexural-slip folds, (2) boudins along thrust contacts, and (3) probable tear faults in the thrust plates. Deformed conglomerates within the Melones fault zone closely resemble in their tectonic style those found in the Clark Mountains area, although this similarity in style does not in itself demonstrate comparable origin.

The majority of the minor folds which occur within the Melones and other fault zones in the Foothills system are slip folds according to the descriptions of Clark (1964, p. 56), Baird (1962, p. 40–44), and to the writer's own limited observations. The steep orientation of many of these slip folds *cannot* be considered evidence in favor of strike-slip movements within the fault zones, even if a steep orientation of the zones since their inception is assumed (which is not the case in this paper). As succinctly stated by Turner and Weiss (1963, p. 485): "The axis of a slip fold has no unique kinematic significance." The orientation of such an axis is defined solely by the line of intersection of the slip surface with a pre-existing surface which behaves passively during deformation. The formation of slip folds with

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[2] Compton (1955, p. 15–16, 43) has suggested that steep lineations in country rocks of the Bald Rock batholith (Fig. 2), western Sierra Nevada, may be due to deformation of the country rocks by vertical extension during emplacement of the pluton. The lineations are defined by long axes of deformed pebbles, hornblende needles, and intersections of cleavages. Compton's interpretation does not seem applicable to similar lineations within fault zones of the Foothills system because of the lack of a consistent spatial association of such lineations to intrusive igneous bodies (a point also made by Clark, 1960, p. 492).

axes nearly parallel to the direction of slip is, therefore, possible. Hansen (1968, p. 536–538), for example, has recently described the presence of slip folds in a Norwegian metamorphic terrane with axes at a mean angle of 5° from the direction of slip, and he has emphasized the invalidity of the concept that fold axes in orogenic belts must be perpendicular to the direction of movement responsible for them. It is geometrically conceivable that steeply plunging slip folds in the Melones fault have formed during westward (now up-dip) slip. Steeply plunging folds with axes parallel to lineations of possible cataclastic origin may also have formed by irregular and subordinate movements perpendicular to a westward slip direction (*compare* Cloos, 1946, p. 26–29; Balk, 1953, p. 102).

Baird (1962, p. 40–44) attempted to determine the direction of slip along surfaces, S'_2, which he believed to be genetically related to the Melones fault zone near Melones, although he is now (A. K. Baird, 1968, written commun.) of the opinion that S'_2 may postdate formation of the fault and be imprinted upon it. Baird's analysis (1962) relied on the pattern of dispersal by rotation of early-formed fold axes during movements on the slip surface S'_2. The intersection of the slip surface (average orientation) and the great circle plane of fold axis rotation uniquely defines the kinematic axis *a*. This axis, according to Baird's analysis, has an orientation in the Melones area of approximately S. 30° E. 12°. Unfortunately, as Baird notes (p. 41), the plane of fold axis dispersal is diffusely defined and intersects the slip surface S'_2 at an angle of less than 25°. Nevertheless, his conclusion that slip on surfaces parallel to the fault zone occurred at a low angle to the present strike of the fault—a direction not parallel to steeper lineations of the type described above—appears warranted. This conclusion does not, however, refute an origin for the Melones fault by thrusting. *If* S'_2 is genetically related to formation of the Melones fault, then Baird's local kinematic analysis could be compatible with a history of thrusting to the northwest, followed by eastward tilting of the fault to its present position. *If*, to the contrary, S'_2 is younger than the fault and has been imprinted upon it, then the direction of slip along this surface may have no relevance to the direction of slip during faulting.

The inconclusiveness of the foregoing discussion on the direction and sense of slip along the Melones fault is clearly unsatisfying, but reflects the paucity of information now available to us. The writer contends that the dip-slip fault versus strike-slip fault controversy of past studies is based on the spurious premise that the fault has always been steeply inclined. He has attempted to demonstrate that minor structures within the Melones fault zone which are now steeply oriented may have formed in a kinematic environment other than that of strike-slip faulting along a subvertical fault zone.

It is probable that the above discussion on the nature of slip along the Melones fault has been too simplistic. This is suggested by the multiple generations of diversely oriented structures found within the fault zone and adjacent terranes. Detailed and careful studies of the Moine thrust zone of Scotland (*compare* Christie, 1963, 1965; Johnson, 1965) serve as a reminder that the kinematic history of major thrust zones can be impressively complex. To conclude, the writer finds nothing in our present state of knowledge about the movement history of the Melones fault to refute its possible correlation with the Trinity thrust of the Klamath province, as based on other criteria discussed in this paper.

CORRELATION OF KLAMATH AND SIERRAN STRUCTURAL BLOCKS

The probable correlation of the eastern Klamath subprovince with the Paleozoic and Mesozoic terrane east of the Melones fault prompts attempts at correlation of other fault-bounded Klamath subprovinces with fault-bounded blocks in the western Sierra Nevada. Such correlations are hindered by the distance of separation between the two regions, by the lack of fossils in their respective eugeosynclinal sequences, and by a dearth of detailed mapping in critical areas. Nevertheless, several possibilities appear worthy of mention.

Metasedimentary and metavolcanic rocks of moderately high grade (up to almandine-amphibolite facies) underlie the Trinity thrust plate (and the Trinity ultramafic pluton) and constitute the central metamorphic subprovince of the Klamath Mountains. Rocks of this subprovince are pre-Devonian in age, based on a Devonian age for their regional metamorphism (380 m.y., Lanphere and others, 1968, p. 1034). This subprovince is considered by the writer to be absent in the northernmost Sierra Nevada. Metamorphosed sedimentary and volcanic rocks in the footwall

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Correlation of the western Paleozoic and Triassic subprovince of the Klamath Mountains with the footwall block of the Melones fault in the northwestern Sierra Nevada appears reasonable. Both terranes are reported to include Paleozoic and Mesozoic eugeosynclinal rocks; both have been extensively intruded by bodies of ultramafic elongated parallel to the structural grain and by younger, isolated granitic plutons. Irwin (1964, p. C7–C8; 1966, p. 33–35) has considered the western boundary of the western Paleozoic and Triassic subprovince to be a thrust fault, although its position in the southern Klamath region is open to question (*compare* Irwin, 1966, his Figs. 1 and 7; Davis, 1966, his Fig. 1). Its structural equivalent in the northwestern Sierra Nevada is most likely the major fault reported to lie between the younger Bald Rock and Merrimac plutons (*see* Fig. 2, this paper; Burnett and Jennings, 1962), although additional field studies are needed to confirm this suggestion. This fault may intersect the Melones fault at approximately 38° 45′ N. latitude (*see* Bateman and Wahrhaftig, 1966, p. 113), thus terminating (at surface level) the Sierran extension of the western Paleozoic and Triassic subprovince (Fig. 1). Alternatively, the Sierran counterpart of this Klamath subprovince may extend much farther south as a narrow strip between the Melones fault and the less well-defined Bear Mountains fault zone to the west. Paleozoic rocks are exposed at a number of localities within this fault-bounded strip, nearly as far south as the latitude of San Andreas (Clark, 1964).

The Klamath western Paleozoic and Triassic subprovince and its probable Sierran equivalent are bordered on the west by comparable terranes of Jurassic sedimentary and volcanic rocks. In the Klamath Mountains, this terrane has been called the western Jurassic subprovince. It consists of the Late Jurassic Galice Formation which has long been considered as correlative with the Mariposa Slate of the western Sierra Nevada (Diller, 1907, p. 404–405; Taliaferro, 1942, p. 77–81, 107; Irwin, 1966, p. 24). Taliaferro (1942, p. 77) states that the "Mariposa and Galice are unquestionable correlatives." Rocks older than the Mariposa Slate are found in the western Sierra Nevada and may be, in part, of Middle Jurassic age (Clark, 1964, p. 16–33). The possible absence of Middle Jurassic rocks in the Klamath western Jurassic subprovince does not weaken the broad correlation of the two terranes suggested here (Fig. 1).

CONCLUSIONS

In summary, boundaries between the Klamath subprovinces are interpreted as thrust faults which steepen southeastward into high-angle faults of the Foothills fault system. Three of the four Klamath subprovinces appear to have stratigraphic and structural counterparts in the northwestern Sierra Nevada. Devonian(?) metamorphic rocks of the central metamorphic subprovince of the Klamath Mountains thin to the north and south in outcrop plan and are apparently not represented in the northwestern Sierra Nevada.

The eastward steepening of the proposed Klamath-Sierran thrust faults is related to their increasing proximity to the Sierran synclinorium and to their rooting into its western flank. Bateman and Wahrhaftig (1966, p. 122–125) and Bateman and Eaton (1967, p. 1408, 1415–1417) have proposed inception of the synclinorium in the Permian or Triassic, marginal faulting of Jurassic age (which includes the Klamath-Sierran faults of this paper), and continued periodic downfolding of the synclinorium into the Cretaceous. The formation of the proposed Klamath-Sierran thrusts thus occurred *during* a lengthy period of profound regional deformation characterized by crustal downbuckling and crustal shortening. The steep dips of thrust faults in the western Sierra Nevada are in large part secondary and attributable to continued development of the synclinorium after thrusting (Burchfiel and Davis, 1968, p. 178, 180). However, primary eastward steepening of the Klamath-Sierran thrusts across the crust is also indicated by the presence of ultramafic rocks along many of them. These rocks, often present in sheet-like bodies, are almost certainly mantle-derived, and their presence along major thrust faults is an indication that the faults have transected the crust and tapped upper mantle peridotites.

Rooting of the Klamath-Sierran faults into a crustal zone undergoing contemporaneous subsidence and shortening clearly rules out an origin for these structures by simple or complex gravitational gliding off an orogenic high (for example, Roberts, 1968, for Great Basin thrusts, or van Bemmelen, 1960, for East Alpine thrusts) or by extrusion ("regurgitation") tectonics from a dilating crustal zone (Carey, 1958, p. 325–331). The proposed correlation of Klamath and Sierran faults, if valid, thus has importance in helping to limit alternatives for the nature of Mesozoic orogenesis in this portion of the Cordilleran orogen.

The geometry, age relationships, and regional setting of the Klamath thrusts have led the writer (1968, p. 930–931) to the conclusion that they are the products of recurrent underthrusting along the western margin of the continent, rather than being "overthrusts" in the more conventional sense. Bateman and Wahrhaftig (1966, p. 125 and their Fig. 2) have discussed the development of the Sierran synclinorium and its marginal faults in terms of possible convective overturn in the mantle, a concept compatible with the idea that the footwall blocks of the Klamath-Sierran thrusts were the most active structural elements. Finally, Burchfiel and Davis (1968) have concluded from the geometry and regional distribution of Cordilleran thrust faults—including the Klamath and possible Sierran examples discussed here—that the westward and eastward bilateral symmetry of post-Paleozoic thrust faulting argues for converging, subcrustal convection cells as the mechanism responsible for Mesozoic and early Tertiary orogenesis in the Cordilleran region. Pre-Cretaceous structural relationships in the Klamath Mountains and western Sierra Nevada provide a key test of this hypothesis.

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