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Structure and tectonics of the northern Sierra Nevada

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ABSTRACT

Recent detailed mapping suggests a new working hypothesis for the structure of the northern Sierra Nevada. We propose that pre-Cretaceous rocks are deformed by a series of eastward-directed overthrusts modified by west-directed folds and faults. The highest and westernmost tectonic unit is the Jurassic Smartville complex. Structurally below it, there are imbricate thrust slices of Jurassic and older ophiolitic and oceanic sedimentary rocks in the Central belt and of Paleozoic to Jurassic sedimentary and volcanic rocks in the Eastern belt. The Paleozoic Feather River peridotite separates the Eastern and Central belts, and our hypothesis suggests that both of its margins may be important thrust faults.

The east-directed faults and folds are deformed by northwest-trending, upright, and west-vergent folds and reverse faults that control the present outcrop pattern. These later structures have so modified the earlier east-directed structures that the latter have been recognized only recently. An important key to understanding the structure has been the recognition of ophiolitic complexes that can be correlated across major faults and that contain a pseudostratigraphy useful in determining local structures. The events recorded by both the east- and west-directed deformations occurred during Callovian through Kimmeridgian time and represent the Nevadan Orogeny.

Our hypothesis of early east-directed overthrusts followed by west-directed back folding and faulting implies shortening and thickening of the crust during the Nevadan Orogeny and is consistent with the idea that the northern Sierra Nevada is the result of a crustal collisional process.

INTRODUCTION

The northern Sierra Nevada is composed of four major tectonic belts, each of which has a different stratigraphy and history of deformation. In this paper, we distinguish (Fig. 1) the Smartville complex (S), the Central belt (CB), and the Eastern belt (EB). The last two belts are separated by a zone containing abundant peridotite, serpentinite, and sporadic occurrences of gabbro and lawsonite-blueschist (Schweickert and others, 1980) that we call the "Feather River peridotite belt (FRPB)." This subdivision of the northern Sierra differs from that used by Schweickert and others (1980).

The most prominent structures within the four belts of the northern Sierra are northwest-trending folds and steeply dipping faults that are especially well-developed in the Eastern, Central, and Feather River peridotite belts, where they have been called the "Foothills fault system" (Clark, 1960) and have been attributed to the "Nevadan Orogeny" of Late Jurassic age (Clark, 1960, 1964). Structures of similar age that deform similar packages of rocks may be traced southward in the western Sierra foothills at least another 200 km, where the four belts of rocks recognized in the north are narrow and so invaded by the Sierra Nevada batholith that their identity is largely obscured (Saleeby, 1982).

The penetrative nature of the Jurassic deformation, especially in the Central and Feather River peridotite belts, for years has plagued efforts to unravel the structure and stratigraphy of the northern Sierra. The problem has been complicated further by the abundant plutons of the Sierra Nevada batholith that were emplaced for the most part during Late Jurassic and Early Cretaceous time (Bateman and Clark, 1974; Bateman, 1981). Only in recent years have working hypotheses been advanced that might serve as unifying guides by which the evolution of the western Sierra could be understood (Moores, 1970, 1972; Moores and others, 1979; Burchfiel and Davis, 1972, 1975; Davis and others, 1978; Schweickert and Cowan, 1975; Schweickert, 1978, 1981; Saleeby, 1978, 1981, 1982).

In this paper, we present a brief overview of the structures and geology of the four major tectonic belts of the northern Sierra Nevada, with special emphasis on the Smartville complex and the Central belt, and we propose a new working hypothesis for the nature of major structures observed in the region. Detailed descriptions of parts of the Smartville complex and Central belt are the subject of several papers in preparation and Ph.D. dissertations in progress, and they will supplement this overview. We propose that there exists in the northern Sierra a stack of eastward-verging thrust sheets or nappes, some of which consist of Mesozoic ophiolitic sequences, and some of which are composed of Paleozoic ultramafic-mafic complexes, volcanic, and sedimentary sequences. We propose, further, that the stack of thrust nappes has been deformed subsequently by steep, west-verging faults and folds that may have formed during episodes of back folding and back thrusting analogous to those observed in the Alps (Milnes, 1974; Debelmas, 1974). According to our hypothesis, prominent northwest-striking foliations and steeply dipping faults in the Foothills fault system may correspond to "steep zones" formed as a late Nevadan feature during the proposed west-verging deformation.

THE SMARTVILLE COMPLEX

The Smartville complex (S in Figs. 1 and 2) (Cady, 1975; Moores, 1975; Schweickert and Cowan, 1975; Xenophontos and Bond, 1978; Menzies and others, 1980) is the westernmost major tectonic unit in the northern Sierra Nevada. It is overlain unconformably on the west by Upper Cretaceous and lower Tertiary unmetamorphosed sedimentary rocks in the Great Valley. On the north and east, the Smartville complex is bounded by a steeply dipping zone of penetrative foliation and faulting that has had a complex history. Units of the Smartville complex continue south of latitude 39°N, but the belt becomes very narrow.

Map Units

The Smartville complex is a remarkably well-preserved section of an ophiolitic sequence that originated in a volcanic arc-marginal basin envi-

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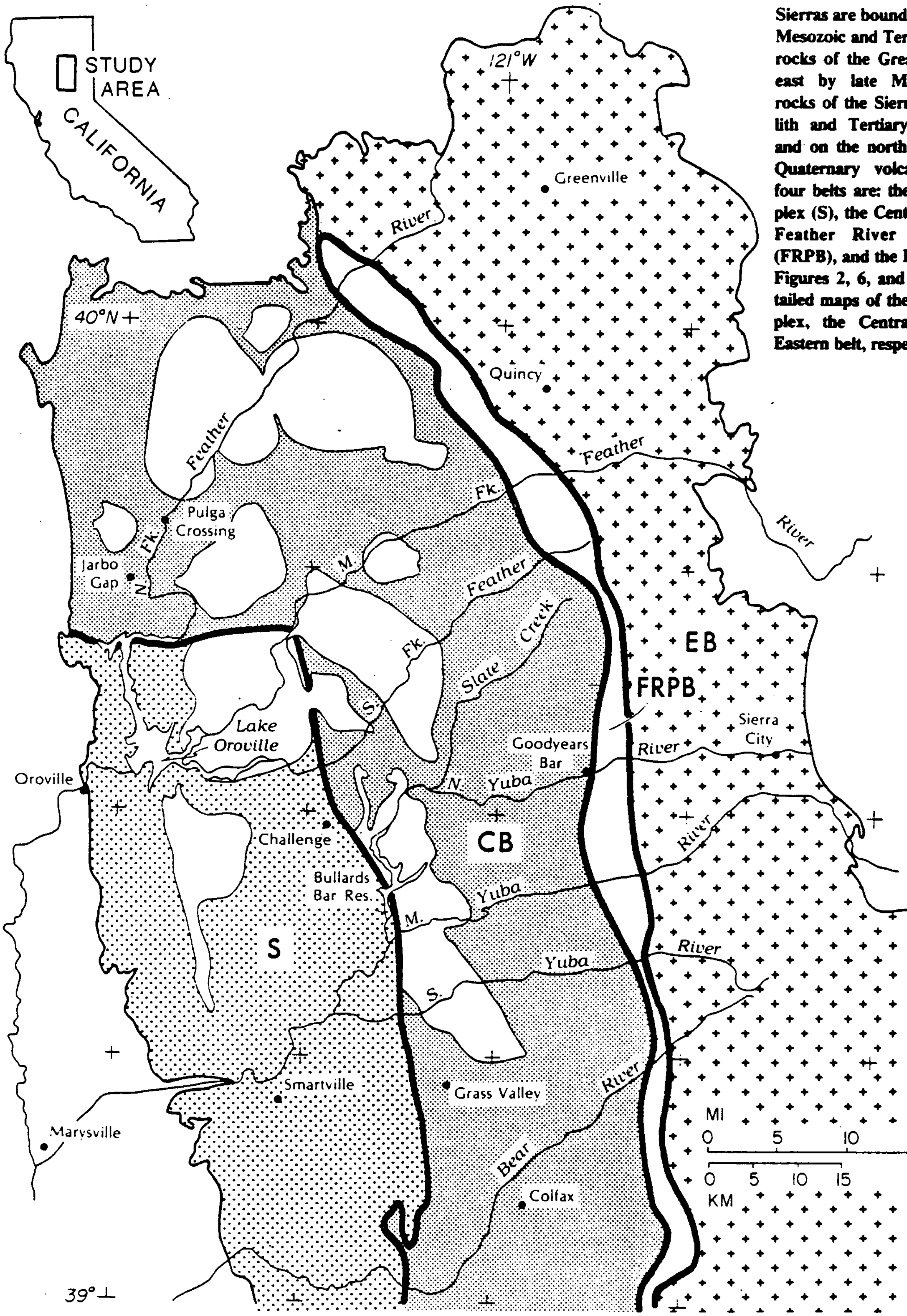

Figure 1. Major tectonic belts of the northern Sierra Nevada. The Sierras are bounded on the west by Mesozoic and Tertiary sedimentary rocks of the Great Valley, on the east by late Mesozoic plutonic rocks of the Sierra Nevada batholith and Tertiary volcanic rocks, and on the north by Tertiary and Quaternary volcanic rocks. The four belts are: the Smartville complex (S), the Central belt (CB), the Feather River peridotite belt (FRPB), and the Eastern belt (EB). Figures 2, 6, and 10 are more detailed maps of the Smartville complex, the Central belt, and the Eastern belt, respectively.

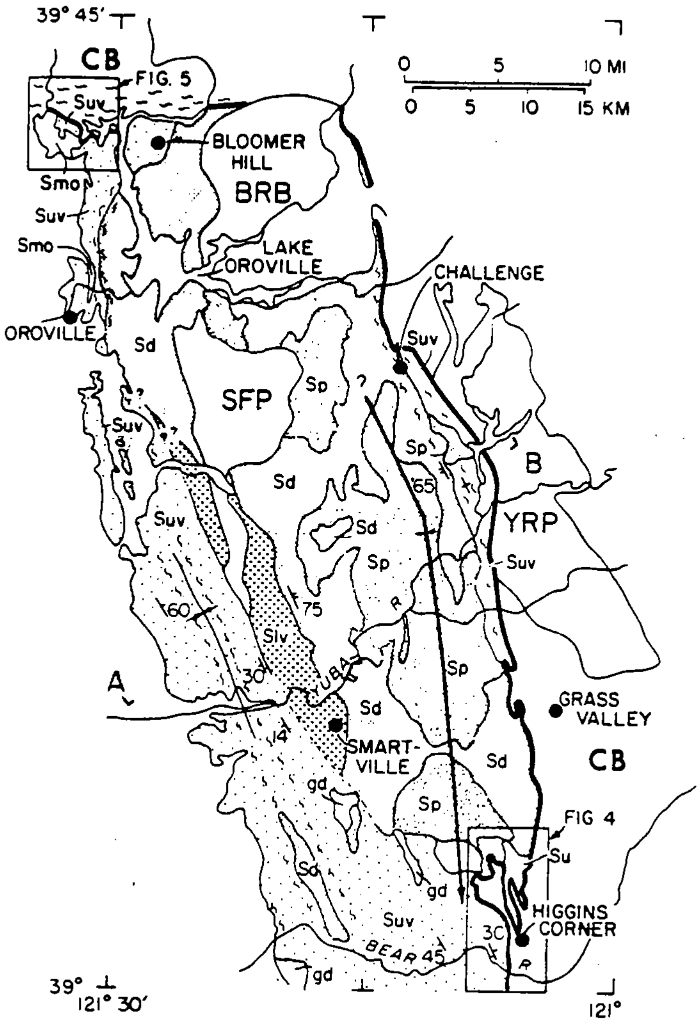

Figure 2. Sketch map of the Smartville complex. Map units: Smo, sedimentary rocks of the Monte de Oro Formation; Suv, upper volcanic unit; Slv, lower volcanic unit; Sd, diabase and dikes; Sp, plutonic rocks; Su, ultramafic rocks. Plutons: SFP, Swedes Flat pluton; BRB, Bald Rock batholith; YRP, Yuba Rivers pluton; gd, granodiorite. CB, Central belt. Attitudes of dikes are shown with a doubly barbed dip symbol.

ronment (Xenophontos and Bond, 1978; Menzies and others, 1980). Figure 2 is a sketch map of this complex based on our own work, as well as on data compiled from Beard and Day (1982, 1983), Bobbitt (1982), Buer (1979), Cole and McJunkin (1979), Compton (1955), Hietanen (1977), Ricci (1983), Vaitl (1980), and Xenophontos and Bond (1978).

The lowermost rocks in the Smartville complex are highly serpentinized ultramafic rocks (Fig. 2) that are best exposed near Higgins Corner. They commonly occur as fault-bounded blocks and are intruded by plutonic and hypabyssal rocks of the Smartville complex. The next lowermost rocks exposed in the Smartville are gabbro and diorite plutons (Sp in Fig. 2). The plutonic rocks are structurally overlain by a massive diabase and by abundant intersecting dikes of diabase and felsite (Sd in Fig. 2). Some outcrops (Day, 1977) are virtually 100% "sheeted" dikes. Along the Yuba River, near Smartville, volcanic rocks are divided into two units that overlie and are intruded by diabase dikes (Xenophontos and Bond, 1978; Menzies and others, 1980; Xenophontos, 1984). The lower volcanic unit (Slv in Fig. 2) contains mainly pillowed and brecciated flows, and the upper volcanic unit (Suv in Fig. 2) is composed primarily of volcanogenic sedimentary rocks. The most striking outcrops of the upper volcanic unit are very coarse volcaniclastic sedimentary rocks containing fragments of pyroxene-phyric-volcanic rocks. The upper volcanic unit includes the Oregon City Formation (Creely, 1965) and the Bloomer Hill Formation (Heitanen, 1977) in the northwest part of the complex, which are shown as Suv in Figure 2. In the northwestern part of the Smartville complex, the upper volcanic unit is overlain by shale, siltstone, and sandstone of the Monte de Oro Formation and equivalent rocks (Smo in Fig. 2) (Creely, 1965; Cole and McJunkin, 1979; Vaitl, 1980).

The ophiolitic pseudostratigraphy of the Smartville has been intruded by later granitic rocks of the Bald Rock batholith, Swedes Flat pluton, Yuba Rivers pluton, and an unnamed granodiorite (BRB, SFP, YRP, and gd in Fig. 2). These granites are widely considered as a western part of the Sierra Nevada batholith (for example, Kistler and others, 1971), but their relationship to the main batholith is poorly understood.

Age

Fossil and radiometric data indicate a Jurassic age for the Smartville and suggest that igenous activity and sedimentation were penecontemporaneous and short-lived. Fossil evidence includes Late Jurassic fossils from the Monte de Oro formation (Creely, 1965), a middle Oxfordian–late Kimmeridgian pelecypod in the "Pentz Sandstone Member of the Calaveras Formation" (Creely, 1965; Marlette and others, 1979), and an Oxfordian-Kimmeridgian ammonite from an outcrop of the Oregon City Formation (Suv in Fig. 2) near Oroville.

Radiometric evidence includes a concordant U/Pb age of 159 m.y. on zircons from the upper volcanic unit at Bloomer Hill (Saleeby, 1981) and U/Pb ages of 155–161 m.y. on zircons from plagiogranite screens in the diabase complex (Saleeby and Moores, 1979; McJunkin and others, 1979). As the Oxfordian-Kimmeridgian boundary is ~158 m.y. old (Armstrong, 1978), the isotopic and fossil ages are in good agreement.

Structure

We interpret the Smartville as a pseudostratigraphic complex similar to ophiolites world-wide (Fig. 3). The rocks within the Smartville complex are, for the most part, only mildly deformed, but the outcrop pattern suggests a broad antiform that plunges gently to the south. The antiform appears to be asymmetrical, with a moderately dipping western limb and a moderately to steeply dipping eastern limb (Fig. 3). The asymmetry sug-

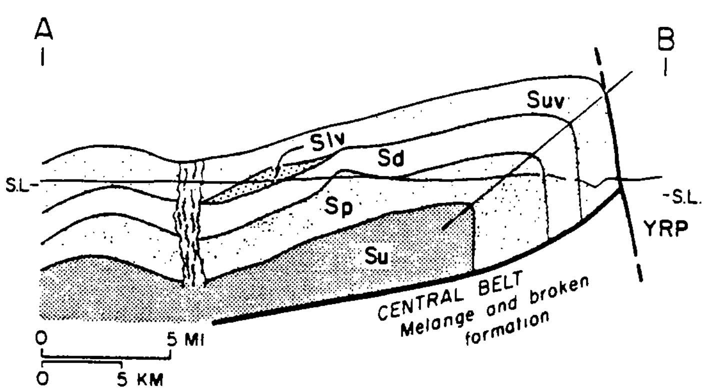

Figure 3. Schematic cross section of the Smartville complex. Section line is A–B in Figure 2. No vertical exaggeration. S.L. marks sea level, and an irregular light weight line marks the present erosion surface.

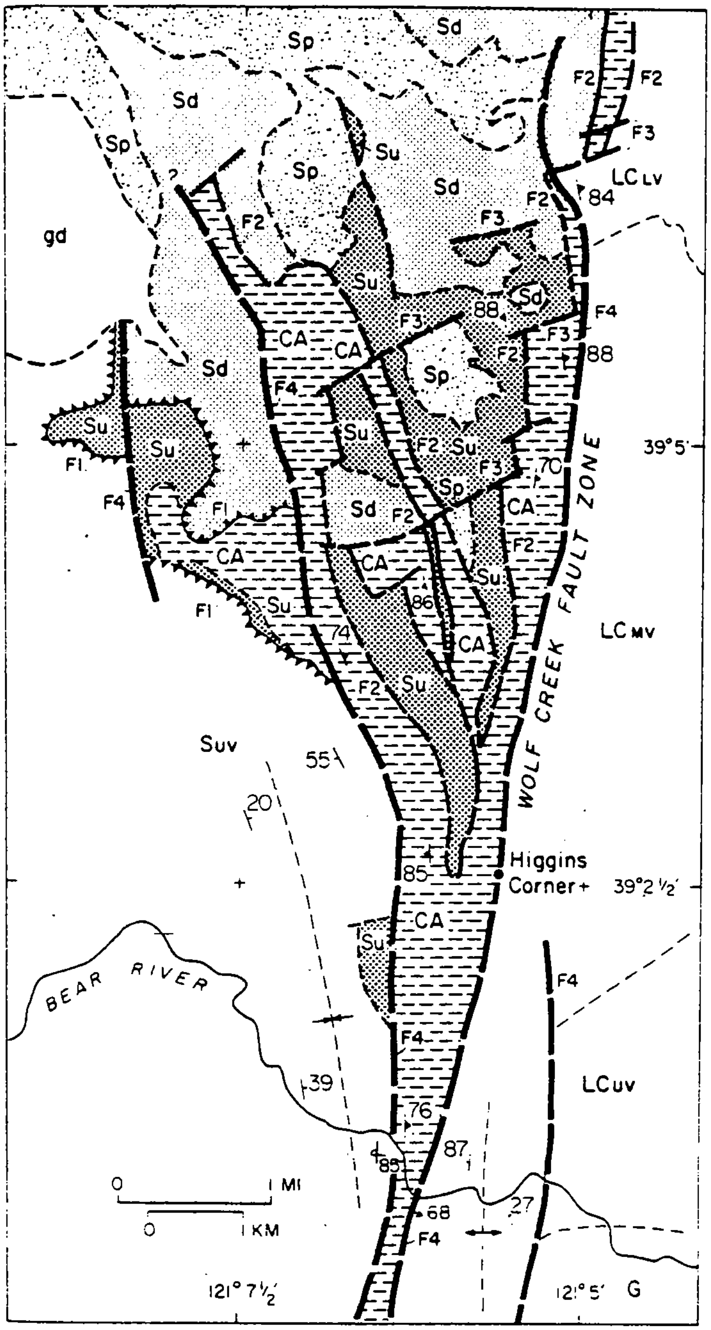

Figure 4. Sketch map of the Higgins Corner area, southwestern Smartville complex. Smartville map units abbreviated as in Figure 2. Central Belt units: CA, chert-argillite broken formation and associated sedimentary rocks; LCuv upper, LCmv middle, and LClv lower volcanic units of the Lake Combie complex; G, granitic pluton. The faulting history is discussed in the section on structure of the Central belt. Barbed lines indicate early (F1) thrust faults; medium-weight dashed lines show high-angle (F2 and F3) faults; heavyweight lines mark the latest steep (F4) faults.

gests that the hinge surface dips moderately west. Farther north, the antiformal outcrop pattern is obscured by later granitic intrusions.

The major exceptions to the relative lack of penetrative deformation in the Smartville rocks are two steeply dipping north-northwest–striking foliation zones. Each zone contains foliation that ranges from a spaced

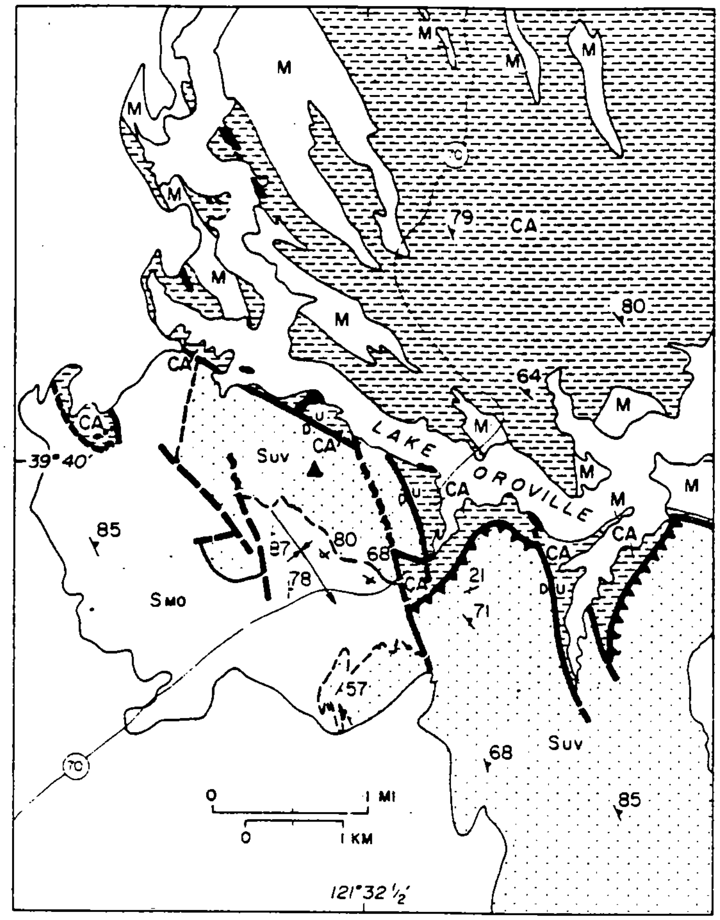

Figure 5. Sketch map of the Smartville complex near Glover Ridge (Δ) modified after Vaitl (1980). Smartville map units abbreviated as in Figure 2. Central Belt units: CA, chert-argillite broken formation and mélange; M, undifferentiated mafic volcanic, sedimentary, and plutonic rocks; dark masses, fossiliferous limestone blocks in CA; unlabeled, undifferentiated post-Jurassic rocks.

cleavage separating relatively undeformed rocks to a penetrative schistosity defined by chlorite and/or actinolite. One of these zones, near the western edge of the Smartville, is as much as 1 km wide; the other, ~2 km wide, marks the eastern margin of the Smartville complex. In places, the eastern zone is more penetratively deformed than the western zone and represents the northern extension of the Wolf Creek fault zone (Tuminas, 1980; Bobbitt, 1982). The western zone extends 60 km southward from Oroville at least to latitude 39°N (Marlette and others, 1979). It contains diverse mafic rocks present as irregular foliated masses that are otherwise similar to undeformed Smartville lithologies. Northwest of Smartville, the zone separates east-dipping rocks of the upper volcanic unit on the west from west-dipping rocks on the east. In that region, we interpret the zone to coincide with the axis of a syncline, as shown in Figures 2 and 3.

The antiformal structure of the Smartville is truncated not only by high-angle faults such as the Wolf Creek fault zone but also by low-angle faults. Low-angle relationships are present near Higgins Corner, at the southeastern margin of the Smartville complex (Fig. 2), where the upper volcanic unit overlies a broken formation of chert and argillite (CA in Fig. 4). Several nearby drill holes penetrate a subhorizontal shear zone separating volcanic rocks above from metasedimentary rocks below (J. W. Motter, 1976, oral commun.), suggesting that the low-angle relationship is a fault.

A deformed low-angle contact may also exist between the northwestern Smartville complex and the Central belt near Lake Oroville and Bloomer Hill (Fig. 2). A detailed gravity survey of the contact in that region (Ricci, 1983) suggested that the Smartville complex forms a slab only a few kilometres thick overlying the chert-argillite rocks of the Central belt. The gravity models of the area further indicate that small plutonic bodies intruding the upper volcanic unit do not extend into the underlying chert-argillite unit. We therefore interpret the contact as a deformed, low-angle thrust fault.

Cole and McJunkin (1979) suggested that a low-angle fault contact is preserved at Glover Ridge (Fig. 5) between rocks of the upper volcanic unit and adjacent chert-argillite of the Central belt and sedimentary rocks to the south, and that Glover Ridge is a klippe. Although we interpret the original contact between the Smartville and the Central belt to be a thrust fault, mapping by Vaitl (1980) at Glover Ridge (Fig. 5) showed that part of Cole and McJunkin's thrust fault is, in fact, a folded depositional contact and that another part is composed of high-angle faults. We thus interpret the sedimentary rocks south of Glover Ridge as Monte de Oro Formation (Smo) overlying the upper volcanic unit rather than as tectonic basement to the latter. East of Glover Ridge (Fig. 5), we interpret the contact between the upper volcanic unit (Suv) and chert-argillite (CA) as a deformed low-angle thrust fault.

THE CENTRAL BELT

The Central belt includes all prebatholithic rocks lying north or east of the Smartville complex and west of the Feather River peridotite belt (Figs. 1, 6). The reconnaissance by Clark (1960, 1964, 1976) and extensive mapping in the northern Central belt by Creely (1965) and Hietanen (1951, 1973, 1976, 1977, 1981) clearly illustrated the stratigraphic and structural complexity of this terrane.

The Central belt is composed of diverse ultramafic, plutonic, volcanic, and sedimentary rocks that have been variably metamorphosed at low or medium grade, affected by one or more periods of isoclinal folding, disrupted by numerous faults, and intruded and metamorphosed by granitic plutons of Late Jurassic to Early Cretaceous age. The resulting assemblage is sufficiently complex that is was summarized by Schweickert and Cowan (1975) in large part as "known mélange."

Recent mapping by us and our colleagues at the University of California, Davis, suggests, first, that within this disrupted terrane there exist large areas of stratigraphically coherent units; second, that some of these coherent units may be tectonic slices of the Smartville complex; third, that the distribution of units and structures may be explained at least in part by early folds and low-angle faults modified by later high-angle faults and folds.

Figure 6 shows our present interpretation of the distribution of major geologic units in the Central belt. The sketch map is based not only on our own work but also on mapping by Hietanen (1951, 1973, 1976, 1977); Burnett and Jennings (1962); and the unpublished work of Vaitl (1980), Jenkins (1980), Zigan (1981), Bobbitt (1982), Mazaheri (1982), Tuminas (1983), Ricci (1983), and S. P. Edelman and B. Hacker (unpub. data).

Chert-Argillite Unit (CA)

A large part of the Central belt is underlain by sedimentary sequences rich in chert and argillite. Included within this unit, there are intercalated slate, argillaceous sandstone, bedded to massive chert, chert breccia, ribbon chert, minor pebbly mudstone and conglomerate, and isolated blocks of fossiliferous limestone. Some of the sedimentary rocks are volcanogenic. The rocks are only weakly metamorphosed, except in contact aureoles,

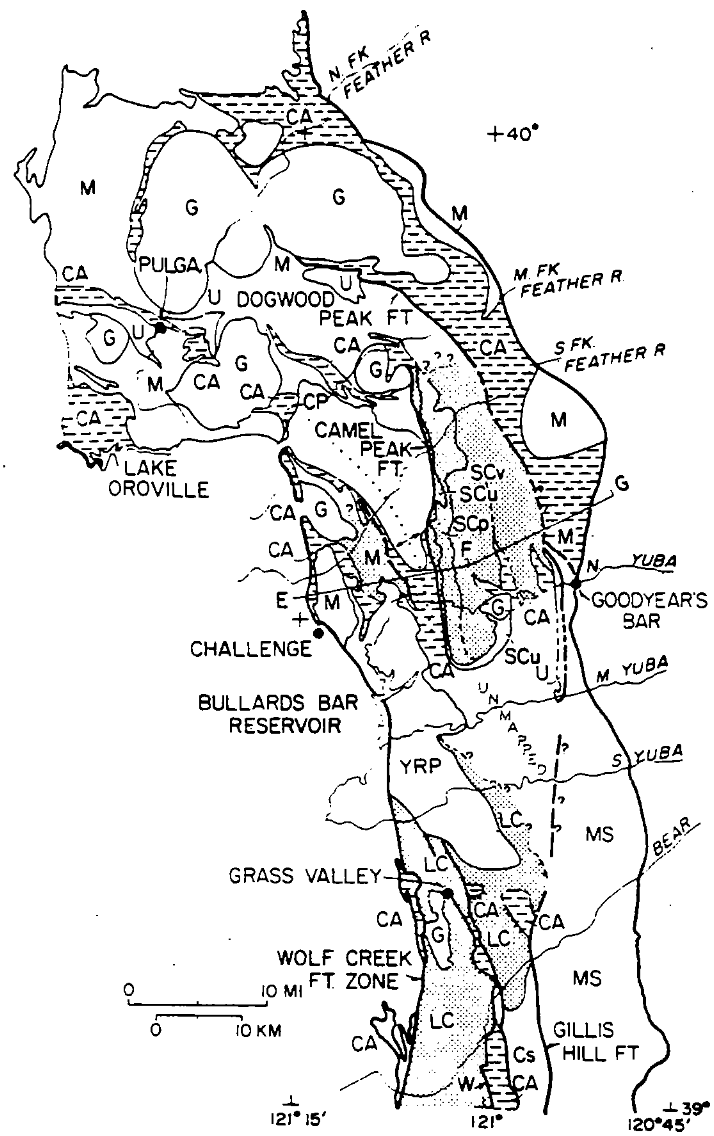

Figure 6. Sketch map of the Central Belt. Map units are summarized in Table 1. Dotted pattern indicates ophiolite pseudostratigraphic complexes similar to the Smartville complex. Dashed-line pattern shows the chert-argillite unit that we interpret as tectonic basement of the overthrust ophiolitic complexes. W indicates the Weimar fault zone.

and relict sedimentary structures are abundant. These rocks in the northern part of the Central belt were mapped variously by Hietanen (1973, 1976, 1977, 1981) as Calaveras Formation and parts of the Duffey Dome, Horseshoe Bend, and Franklin Canyon Formations.

Vaitl (1980) gave a detailed description of this unit near the northwest end of Lake Oroville, where it was mapped as Calaveras Formation by Creely (1965), and interpreted it to be a shale matrix mélange (Fig. 5). In the Grass Valley area, this unit was called the Clipper Gap Formation of the Calaveras "Group" (Lindgren, 1900; Chandra, 1961), and work by Tuminas (1983) indicated that it is best described as a broken formation. Although tectonic disruption was probably important in both areas, the presence of carbonate clasts in pebbly mudstones suggests that large lenticular masses of limestone possibly were incorporated into the chert-argillite by sedimentary gravity debris slides.

Vaitl (1980) showed that massive volcanic rocks and volcanic breccias and tuffs, as well as gabbro and serpentinite, occur in the chert-argillite unit as fault-bounded blocks as much as 2 km long. Tuminas (1980, 1983) also demonstrated that pyroclastic and volcanic rocks, as well as polymict conglomerates, are fault-bounded slices of rocks lithologically similar to units in the younger Smartville complex, Lake Combie complex, and Colfax sequence (see discussion below). In the Grass Valley area, furthermore, volcanogenic or plutonic detritus is not a component of sedimentary rocks in the chert-argillite unit. Volcanic and plutonic rocks thus probably were included within the chert-argillite unit primarily by tectonic processes.

Age. The limited age information for the chert-argillite unit includes late Paleozoic corals from exposures of marble in the Bear River (Lindgren, 1900); probable late Paleozoic corals from limestone near the South Yuba River and some Pennsylvanian(?) gastropod molds in "massive tuff" from the same region (Clark, 1976, p. 12); late Paleozoic corals from a limestone lens north of Oroville (Creely, 1965, p. 18); and Pennsylvanian-Permian fossils in limestone near the Middle Fork Feather River (Hietanen, 1981). The limestone lenses probably are blocks in mélange, and they set only a maximum age for the time of their incorporation into the mélange. Irwin and others (1978) identified Upper Triassic or Jurassic radiolaria from cherts along the North Fork Feather River, and Hietanan (1981) reported radiolaria in chert from two localities near the North Yuba River as being Triassic to Lower Jurassic and Middle to Upper Triassic, respectively. At least part of the chert-argillite unit thus is younger than the included limestone blocks.

Lake Combie Complex (LC)

The Lake Combie complex (Fig. 6) is a fault-bounded belt of Jurassic mafic igneous and sedimentary rocks that are interpreted to have formed within an oceanic island arc (Tuminas and Moores, 1981; Tuminas, 1983). On the west, the complex is in fault contact with the Smartville complex along the Wolf Creek fault zone. On the east, the Lake Combie complex is in fault contact with the Colfax sequence (Cs) and the chert-argillite unit (CA) along the Weimar fault zone (W in Fig. 6) and with undifferentiated metasedimentary rocks (MS) along the Gillis Hill fault zone (Chandra, 1961; Tuminas, 1983).

Figure 7 is a sketch map of the Lake Combie complex in the Grass Valley–Colfax area. The structurally lowest unit of the Lake Combie complex is an ultramafic tectonite (LCu in Fig. 7) of foliated and lineated harzburgite, pyroxenite, and dunite. The ultramafic tectonite unit is intruded and overlain structurally by a mafic plutonic unit ranging in composition from gabbro to quartz diorite (LCp in Fig. 7). Mafic to intermediate hypabyssal dikes are common in the plutonic unit and locally make up a zone of 100% nonsheeted dikes and massive diabase near the top of the plutonic unit (LCd in Fig. 7). The plutonic and diabase units are overlain by a thick (>5 km) sequence of mafic rocks that grades upward from primarily volcanic flows near the base to primarily volcaniclastic and epiclastic sedimentary rocks near the top (LClv, LCmv, and LCuv in Fig. 7). The upper volcaniclastic and epiclastic units include massive flow rock (rarely pillowed), flow breccia, pyroclastic flow breccia, pyroclastic tuff, mudflow breccia, and volcanogenic turbidite sandstone. Despite the complex internal stratigraphy of the volcanic sequence, the abundance of pyroclastic debris suggests voluminous explosive volcanism.

Age. No fossils have been found in the Lake Combie complex, but broadly similar rock types, found farther south along the strike of this fault-bounded belt, have Middle Jurassic (Callovian) fossils (Imlay, 1961; Clark, 1964, 1976). Near Nevada City, the Lake Combie complex is intruded by the Yuba Rivers pluton, which has an apparent age of 150 m.y. (K-Ar on hornblende, recalculated from Evernden and Kistler, 1970). The arc activity in the Lake Combie complex thus is constrained to be pre–Late Jurassic, possibly Callovian.

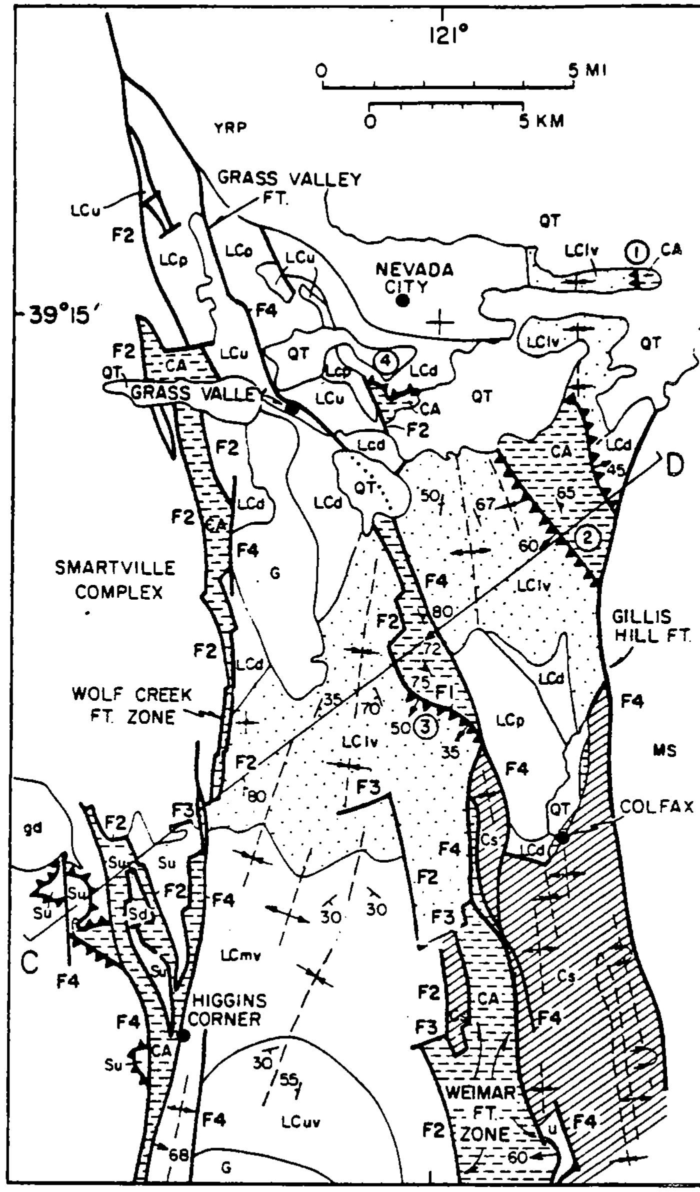

Figure 7. Sketch map of the Grass Valley–Colfax region. Lake Combie complex: LCuv, LCmv, LClv upper, middle, and lower volcanic units; LCd, diabase and dikes; LCp, mafic plutonic rocks; LCu, ultramafic rocks. Cs, Colfax sequence of sedimentary rocks; QT, Quaternary and Tertiary undifferentiated. Fault designations are discussed in the text. Other units as in Figures 2 and 6.

We interpret the Lake Combie complex as a pseudostratigraphic sequence representing an island-arc assemblage (gabbro, diabase, and volcanics) constructed upon a pre-existing, disrupted oceanic lithosphere (the ultramafic tectonite). The similar age, lithology, and stratigraphy of the Lake Combie and the Smartville lead us to believe they were part of the same Jurassic oceanic-volcanic complex.

Colfax Sequence (Cs)

The Colfax sequence (Figs. 6 and 7) is a fault-bounded belt of Late Jurassic flysch (Tuminas and Moores, 1982; Tuminas, 1983). It is bounded on the west by the chert-argillite unit and the Lake Combie complex along the Weimar fault zone and on the east by undifferentiated metasedimentary rocks (MS) along the Gillis Hill fault (Chandra, 1961). These rocks were mapped as Mariposa Formation by Chandra (1961).

The Colfax sequence consists of interbedded conglomerate, sedimentary breccia, sandstone, shale, and minor tuff. Sedimentary structures, such as graded bedding, cross-bedding, convolute bedding, and laminated bedding associated within partial to complete Bouma sequences, indicate that these sedimentary rocks were deposited as turbidity current deposits in deep-sea fan-channel complexes (Tuminas and Moores, 1982). The ubiquitous development of channelized bedding and thinning-and-fining-upward sequences indicates that deposition was in inner-fan to suprafan environments of the submarine-fan model (Walker and Mutti, 1973; Mutti and Ricci-Lucchi, 1976). Abundant soft-sediment deformation structures and debris-flow deposits indicate a basin geometry with unstable, steep flanks (Tuminas, 1983). The Colfax sequence probably was deposited in relatively small (2 by 10 km), elongate basins associated with early pulses of Nevadan deformation; if so, it represents a syntectonic flysch deposit (for example, Hsu, 1968).

The relation of the Colfax sequence to the Lake Combie complex is not certain. The Weimar fault zone and other faults mark the contact between the units, but distal air-fall tuffs intercalated in the basal part of the Colfax sequence are similar to those found in the Lake Combie, suggesting a possible minor interfingering between Colfax sequence and Lake Combie complex. The relation of the Colfax sequence to the chert-argillite unit is exposed just north of the town of Colfax, where conglomerates of the Colfax sequence rest unconformably upon tightly folded chert and argillite. Abundant chert-argillite detritus within the Colfax sedimentary rocks also suggests erosion of the chert-argillite unit during Colfax deposition.

Petrographic studies of the Colfax sequence (Tuminas, 1983) indicate that it was derived from a metamorphic-sedimentary-tectonite terrane; volcanic detritus is notably uncommon. The volcanic provenance of epiclastic rocks in the Lake Combie complex (Tuminas, 1983) is distinct from the nonvolcanic provenance of the Colfax strata. We believe, therefore, that the Lake Combie complex and the Colfax sequence were deposited, for the most part, in different areas that were later juxtaposed tectonically.

Age. The Colfax sequence is Late Jurassic in age. Imlay (1961) reported Callovian and upper Oxfordian to lower Kimmeridgian fossils in sedimentary rocks near Colfax, but we have been unable to find the fossil localities. Chandra (1961) and Clark (1976) correlated the deposits in the Colfax area with the Late Jurassic Mariposa Formation farther south. We believe that the Colfax sequence is the same age as the lithologically similar Mariposa rocks, but broad-scale correlation of such sedimentologically and structurally complex rock sequences is probably unwarranted at this time.

Slate Creek Complex (SC)

Farther north in the Central belt, there is another relatively intact belt of rocks that we call the "Slate Creek complex" (SCv, SCp, and SCu in Fig. 6). It corresponds, in part, to rocks mapped by Hietanen (1973, 1976) as "Franklin Canyon Formation." On the west, it is bounded by a major fault zone corresponding in part to the Camel Peak fault of Hietanen (1976, 1981) and by deformed and metamorphosed sediments of the chert-argillite unit. On the east, the sequence is bounded by the Dogwood Peak fault (Hietanen, 1973, 1981), which separates the Slate Creek complex from the chert-argillite unit on the east. We have not yet traced this fault south of the North Yuba River.

The Slate Creek complex is a pseudostratigraphic succession of ultramafic, igneous, and sedimentary rocks. The structurally lowest unit of the Slate Creek sequence is highly deformed and serpentinized ultramafic rocks (SCu in Fig. 6) consisting of massive antigorite-serpentinite and minor peridotite. The serpentinite may have been metamorphosed by the intrusion of the Cascade pluton (CP in Fig. 6) on the west and by metaplutonic rocks (SCp in Fig. 6) on the east. Near the South Fork of the Feather River, where deformation is great, the serpentinite contains inclusions of gabbro, amphibolite, quartzite, and metavolcanic rocks surrounded by talc-chlorite schist and was interpreted by Zigan (1981) as an ultramafic mélange. Farther south, however, the ultramafic unit seems more intact (Jenkins, 1980).

The ultramafic unit is intruded and structurally overlain by hornblende-bearing metaplutonic rocks (SCp in Fig. 6) ranging in composition from gabbro to tonalite. These plutons are variably deformed and metamorphosed and, as mentioned above, have produced contact metamorphic zones where they intrude the ultramafic rocks (Jenkins, 1980). Near the top of the plutonic sequence, greenstone dikes make up no more than 10% of the outcrops in which they are present (Zigan, 1981). This relationship contrasts with the extensive zones of massive diabase and dikes found in the Smartville complex and the Lake Combie sequence.

The plutonic unit is overlain by an east-dipping sequence of volcanic and sedimentary rocks (SCv in Fig. 6) that seems to be substantially intact and only weakly metamorphosed. The base and top of the sequence are composed of aphyric, plagioclase-phyric, or pyroxene-phyric massive and pillowed flows and flow breccias of intermediate composition. Interbedded sedimentary breccias, slate, chert, tuff, and volcanogenic sandstone constitute the middle of the sequence. The sequence contains deformed zones that may be faults, but we have found no evidence for major offset. The Dogwood Peak fault, however, separating the upper part of the Slate Creek complex from the chert-argillite unit to the east, is a major feature that is marked by extreme deformation of the volcanic rocks and total destruction of original fabrics and mineralogy.

We have not yet examined this entire belt of rocks, but our reconnaissance and mapping by S. Edelman and B. Hacker (unpub. data) indicate that the complex continues south of the North Yuba River. The mapping of Hietanen (1973, 1976) suggests that it continues at least as far north as the Middle Fork of the Feather River, a total distance of at least 30 km. The observed pseudostratigraphic association of plutonic, volcanic, and volcaniclastic rocks suggests that the Slate Creek complex may also represent a volcanic arc built upon oceanic lithosphere represented by the serpentinized ultramafic rocks. An important difference from the Lake Combie and Smartville complexes, however, is the lack of a dike or diabase unit in the pseudostratigraphy.

Age. Hietanen (1981) reported isotopic ages (K-Ar, hornblende) of 148 ± 7.4 and 161.9 ± 8 m.y. from a gabbro on Slate Creek that is part of the plutonic unit (SCp). The Slate Creek complex thus appears to be approximately the same age as the Smartville and Lake Combie complexes.

Undifferentiated Metasedimentary Rocks (MS)

East of the Gillis Hill fault (Fig. 6) in the southern part of the Central belt, there is a large tract of multiply deformed, disrupted, and metamorphosed rocks that is bounded on the east by the Feather River peridotite belt. The northward extent of these rocks and the Gillis Hill fault are at present unknown.

The metamorphosed rocks include three major protoliths that are indicated in Figure 6 and Table 1 as undifferentiated metasedimentary and volcanic rocks (MS): volcanic rocks, pebbly mudstone, and chert. The sequence is steeply east-dipping. Rare stratigraphic top indicators suggest that the volcanic rocks lie at the base and the chert at the top of the sequence. The contacts between the three major rock types are marked by the gradual increase in the proportions of the overlying lithologies. The volcanic rocks consist of interbedded tuffaceous mudstone (argillite and slate), tuff (chlorite-amphibole phyllite), tuff-breccia, and both massive and pillowed flows. The most abundant rock types are the tuffaceous rocks

TABLE 1. MAP UNITS IN THE CENTRAL BELT

Unit	Unit name	Description
Cs	Colfax sequence	Upper Jurassic flysch
LC	Lake Combie complex	Upper Jurassic ophiolitic pseudostratigraphic sequence
SC	Slate Creek complex	Upper Jurassic ophiolitic pseudostratigraphic sequence containing ultramafic (SCu), plutonic (SCp), and volcanic and sedimentary rocks (SCv)
M	Undifferentiated mafic rocks	Upper Jurassic and older mafic volcanic and plutonic rocks, volcanogenic sedimentary rocks, and associated ultramafic rocks
U	Undifferentiated ultramafic rocks	Mesozoic(?) and older(?) peridotite, dunite, and serpentinite
CA	Chert-argillite	Upper Paleozoic to Lower Jurassic sedimentary rocks including chert, shale, sandstone, and limestone. Includes some volcanogenic sandstone, shale, and tuff.
MS	Undifferentiated metasedimentary and volcanic rocks	Upper Paleozoic(?) or younger volcanogenic slate and phyllite; phyllitic, pebbly mudstone; metachert and quartzite
G	Undifferentiated plutons	Upper Jurassic–Lower Cretaceous post-tectonic granodiorite, tonalite, and gabbro
CP	Cascade pluton	Upper Jurassic–Lower Cretaceous tonalite and trondhjemite
YRP	Yuba Rivers pluton	Upper Jurassic late-tectonic tonalite, granodiorite, and granite

(phyllite). The overlying pebbly mudstone is composed primarily of muscovite phyllite containing between 5% and 30% metavolcanic, metaplutonic quartzite, and metachert clasts flattened in the plane of the foliation. Metasedimentary clasts may have been more abundant than is now apparent and selectively obliterated during deformation. The uppermost unit consists chiefly of thin-bedded (1–20 cm) metachert and siliceous phyllite. Tuminas (1983) suggested that this sequence represents immature deep-water debris flows deposited on a volcanic basement.

Age. The age of these metasedimentary rocks is unknown. Lindgren (1900, p. 2) reported Paleozoic(?) crinoid stems from a small limestone body about 1 mi northeast of Colfax. Limestone is found only as isolated masses in the metasedimentary rocks, however, and for the chert-argillite unit may have been included at a later time by tectonic or sedimentary processes.

Undifferentiated Ultramafic and Mafic Rocks (U, M)

Undifferentiated ultramafic and mafic rocks of unknown ages are abundant in the Central belt. Undifferentiated mafic rocks (M) include mafic rocks of plutonic, volcanic, and sedimentary origin, as well as small bodies of serpentinite too small to show at the scale of Figure 6. The unit includes parts of the Duffey Dome, Horseshoe Bend, and Franklin Canyon Formations, as well as amphibolite adjacent to the Feather River peridotite belt (Hietanen, 1973, 1976, 1977, 1981). Only large bodies of ultramafic rock are shown as undifferentiated ultramafic rocks (U). The undifferentiated ultramafic and mafic rocks commonly are mixed intimately with metasedimentary rocks along tectonic contacts, especially with the chert-argillite unit.

Exposures of ultramafic rocks range in size from a few square metres to tens of square kilometres. The rocks are, for the most part, deformed and serpentinized, and they invariably are associated with mafic metavolcanic or metaplutonic rocks. Dunite, pyroxenite, clinopyroxenite, and peridotite have been identified as protoliths of the serpentinized ultramafic rocks. Serpentine sandstones have been identified at several localities northeast of Challenge and are included in the Undifferentiated Ultramafic Rocks (Fig. 6).

Mafic lithologies associated with the ultramafic rocks include coarse-grained metaplutonic rocks, as well as fine-grained greenstones, greenschists, and amphibolites the protolith of which is commonly impossible to ascertain. Metagabbro and metadiorite bodies with gneissic fabrics and mineral assemblages typical of the epidote-amphibolite and amphibolite facies of metamorphism are common (Hietanen, 1973, 1976, 1977; Mazaheri, 1982). Mazaheri (1982) argued that gneissic metagabbro at Pulga (Fig. 6) intruded serpentinite, and that the gneissic fabric and amphibolite-facies mineral assemblages are overprinted by Nevadan foliations and greenschist-facies mineralogy. He suggested that the Pulga mafic and ultramafic rocks are older than the 160-m.y.-old Smartville complex, because the gabbro contains evidence for a pre-Nevadan mineralogy.

Granitic Plutons

Numerous plutons ranging in composition from gabbro to granodiorite intrude the deformed igneous and sedimentary rocks in the Central belt. Most of these plutons appear to be post-tectonic and have apparent ages (K-Ar, biotite, hornblende) suggesting that they were intruded during Early Cretaceous time (Evernden and Kistler, 1970; recalculated using tables of Dalrymple, 1979). The Yuba Rivers pluton (YRP, Fig. 6), however, appears to be Late Jurassic in age (150 m.y., K-Ar on hornblende) (Evernden and Kistler, 1970; Dalrymple, 1979).

Relationship of the Smartville, Lake Combie, and Slate Creek Complexes

The Smartville, Lake Combie, and Slate Creek complexes have many features in common, suggesting that they are part of an originally continuous ophiolitic terrane. Each complex is a pseudostratigraphic succession of ultramafic, plutonic, hypabyssal, and volcaniclastic rocks. The available evidence indicates that each is Middle or Late Jurassic. Mafic to intermediate plutonic rocks in each complex intrude structurally lower serpentinized ultramafic rocks and structurally overlying volcanic rocks. Volcanic rocks in each complex contain important amounts of pyroclastic material and subordinate pillowed and massive flows containing plagioclase and clinopyroxene phenocrysts. Epiclastic strata primarily are volcanogenic turbidites. Finally, none of these complexes, in contrast to some undifferentiated mafic rocks, has suffered high-grade regional metamorphism or penetrative deformation (except near major faults).

Some differences among the complexes exist. The Lake Combie complex contains a higher proportion of layered gabbro than do the plutonic suites of the other complexes. The Smartville complex contains extensive zones of both sheeted and unsheeted dikes, whereas the Lake Combie complex contains only unsheeted dikes, and the Slate Creek complex has neither a well-developed set of dikes nor a diabase suite. Volcanic flows in the Smartville and Slate Creek complexes commonly have pillow structure, whereas virtually all flows in the Lake Combie complex are massive or brecciated. It appears to us, however, that these differences are within the expected range of variations in a laterally extensive oceanic volcanic-arc terrane.

Some areas of now undifferentiated mafic rocks may prove, upon careful examination, to be similar to the three complexes we have described. As discussed below, Murphy (1984) examined the undifferentiated mafic rocks adjacent to the southwestern part of the Cascade pluton (CP, Fig. 6) and found that they represent a *west*-facing pseudostratigraphic sequence similar to the Slate Creek complex. As noted previously, other undifferentiated mafic rocks such as those near Pulga are apparently older than the Smartville terrane.

Structure of the Central Belt

The Central belt is disrupted by numerous high-angle faults that separate the major geologic units discussed above and that commonly are associated with zones of penetrative foliation. This intense disruption and the lack of prominent markers that can be correlated across the major faults have hampered efforts to unravel the regional structure. Our ability to attack this difficult problem and to offer the working hypotheses presented in this paper has been enhanced by three recent developments, however. First, as outlined above, the recognition that the Smartville complex and other areas in the Central belt are ophiolitic pseudostratigraphic sequences permits a fresh look at the major structures over relatively large areas. Second, the recognition that several ophiolite sequences in the Central belt may correlate with the Smartville complex provides us, for the first time, with a stratigraphic and structural marker horizon that can be correlated across major faults. Finally, detailed work by Tuminas (1980, 1983) in the Grass Valley–Colfax area suggests that a recognizable sequence of faulting exists that may form a basis for beginning to understand the deformation of the Central belt farther north.

Grass Valley–Colfax Area. Studies in the Grass Valley–Colfax area indicate at least four generations of faults: (1) F-1, subhorizontal to moderately dipping faults; (2) F-2, steep faults that strike northwest and dip west; (3) F-3, subvertical right separation faults that strike east or northeast; and (4) F-4, steep faults that strike north and dip east. We interpret the early F-1 and F-2 faults as east-directed thrust and reverse faults and the later F-4 generation as west-directed reverse faults.

Low-angle (F-1) faults occur at localities numbered 1 to 4 (Fig. 7). At each place, Lake Combie rocks structurally overlie the chert-argillite (CA). The contacts do not crop out, but their topographic expression and the truncation of lithologic units along them indicate a low-angle fault, with variable dips (0° to 60°) both to the east and the west. Direct evidence for the sense of displacement on the low-angle faults is not available. The correlation of the Lake Combie rocks in the upper plate with the Smartville complex to the west and the lack of similar rocks east of the Lake Combie complex, however, suggest that the upper plate was transported from the west.

F-2 faults are especially abundant in the Wolf Creek and Weimar fault zones (Fig. 7). Such faults consistently dip west and are associated with tight folds and overturned bedding. Well-developed foliation or mylonitic fabric commonly occurs parallel to the faults and defines a downdip extension direction (Tuminas, 1980, 1983). Such fabrics are not typical of high-angle normal faults and are consistent with reverse movement. The relationship of F-1 and F-2 faults is uncertain. At locality 3 (Fig. 7), the F-1 fault progressively steepens to the northwest, where it is mapped as an F-2 fault because of its steep dip. This relationship suggests that F-2 faults may be low-angle faults that were later steepened. Alternatively, the F-2 faults may be steep ramps associated with the F-1 thrust faults.

F-3 faults are also abundant in the Wolf Creek and Weimar fault zones, where they displace the traces of F-2 faults by 50–700 m, usually in a right-lateral sense (Tuminas, 1983). It seems reasonable that the slip and separation on the F-3 faults are comparable both in sense and magnitude, because the east-trending F-3 faults are subvertical, and the F-2 faults they offset are steep. F-3 faults are truncated by F-4 faults and, because they offset F-2 faults, are interpreted as an intermediate generation of faults.

F-4 faults include the Gillis Hill and Grass Valley faults, as well as unnamed faults in the Wolf Creek and Weimar fault zones (Fig. 7). F-4 faults are distinguished from F-2 faults because: (1) they consistently dip 60° to 80° east; (2) they are not offset by F-3 faults; (3) well-developed foliation and mylonite in the hanging wall are generally absent; and (4) they are sharply defined and laterally continuous for 5–20 km and truncate all other faults in the area (Tuminas, 1983). The displacement on the Gillis Hill fault is apparently reverse, based on the fact that folds in the Colfax sequence become tighter and overturned to the west near the fault. Chandra (1961) suggested as much as 4 km of reverse displacement on the Gillis Hill fault. The F-4 faults in the Grass Valley, Wolf Creek, and Weimar fault zones show no evidence for major offset, because they commonly juxtapose rocks of the same unit, and fault-related tectonite or mylonite are generally absent.

The absolute and relative ages of the various faults can be ascertained in an area just northwest of Nevada City (Fig. 7). In that area, F-2 faults and associated mylonite are truncated by the Yuba Rivers pluton (150 m.y.; K-Ar age on hornblende recalculated from data of Evernden and Kistler, 1970). The western margin of the Yuba Rivers pluton and its contact aureole are deformed by F-4 faults. Greenschist-facies mineral assemblages in the contact aureole define a foliation parallel to the fault and parallel to a gneissic foliation in the western margin of the Yuba Rivers pluton that is mylonitic in places. We infer that the fault was active, and that the foliation was formed during the cooling of the pluton. The F-2 faults thus postdate the 160-m.y.-old Smartville complex and predate the 150-m.y.-old Yuba Rivers pluton, and the F-4 faults may be essentially synchronous with the 150-Ma cooling of the pluton.

Folds in the Grass Valley–Colfax area are difficult to trace and their relationship to the faulting episodes poorly understood, because prominent marker horizons are absent. The volcanic units of the Lake Combie complex (LClv, LCmv, and LCuv in Fig. 7) display a series of broad, upright, and open folds. The only mesoscopic structure associated with the folds is an irregular, spaced cleavage in the hinge areas. The Colfax sequence (Cs) contains abundant folds that range from moderately open and upright to tight and overturned to the west. A slaty, axial-plane cleavage is prominent on the overturned limbs of major folds. The chert-argillite (CA) contains abundant mesoscopic isoclinal folds with a slaty axial-plane cleavage in argillaceous rocks and a spaced axial-plane cleavage in more siliceous rocks.

The ages of the folds are poorly constrained. The folded contact between the upper and middle volcanic units southeast of Higgins Corner (Fig. 7) is truncated by a steep F-4 fault. In the Colfax sequence, however, tightening and overturning of folds to the west are clearly related to the (F-4) Gillis Hill fault. The isoclinal folding in the chert-argillite unit may be older and related to the disruption of the unit to create a broken formation.

Figure 8 is a cross section illustrating our interpretation of the Grass Valley–Colfax area as a stack of east-vergent thrust faults disrupted by west-directed high-angle reverse faults. In the west, low-angle faults separate units of the Smartville complex (Suv, Sd, Su) from each other and from underlying chert-argillite (CA). Some contacts between diabase (Sd) and serpentinite (Su) may be intrusive. West of the Wolf Creek fault zone (WC in Fig. 8), we infer that units of the Lake Combie complex underlie the chert-argillite and the Smartville complex, because the latter overlie the Lake Combie complex along west-dipping F-2 faults north of the line of section (Fig. 7). Between the Wolf Creek (WC) and Weimar (W) faults, we show two major slices of Lake Combie complex with a slice of chert-argillite intervening. The existence of the lower slice of Lake Combie complex is inferred from the presence of Lake Combie rocks east of the Weimer fault that were uplifted to their present position by reverse movements on this F-4 fault. Notice that the amount of reverse movement illustrated on the Wolf Creek and Weimar fault zones is small.

Northern Part of the Central Belt. It is not yet clear how structures in the northern part of the Central belt correlate with the structures observed in the Grass Valley–Colfax area. At least two major fault zones in the north, however, may be throughgoing features that connect with faults in the Grass Valley–Colfax area.

The major fault zone that forms the eastern margin of the Smartville

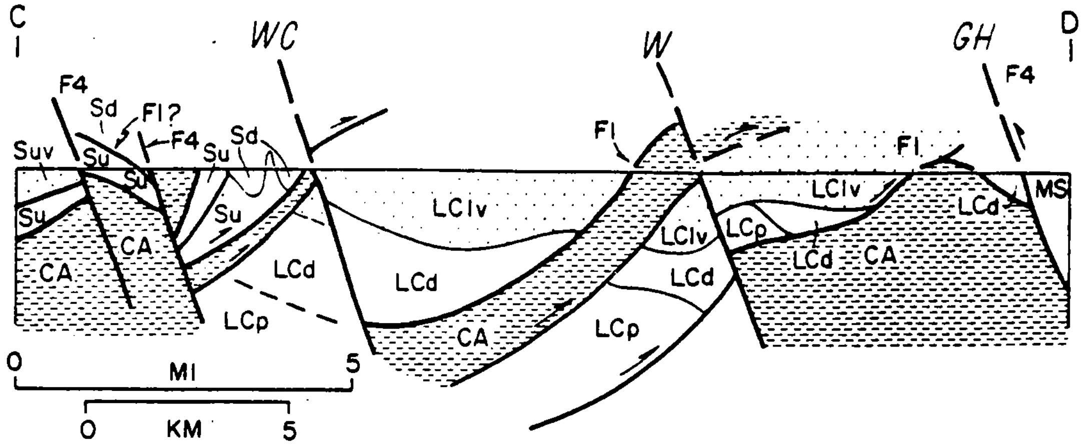

Figure 8. Cross section through the Grass Valley–Colfax area. The line of the cross section is C–D in Figure 7. Units as in Figure 7. No vertical exaggeration. Minor relief on the topographic surface.

complex is the northern extension of the Wolf Creek fault zone. North of the Grass Valley area in the vicinity of the Bullards Bar reservoir (Fig. 6), Smartville rocks are intruded by the Yuba Rivers pluton, and the intrusive contact between the two units has been overprinted by an east-dipping foliation associated with F-4 faulting. North of the Yuba Rivers pluton near Challenge (Fig. 6), the eastern margin of the Smartville complex is an intensely deformed zone ~2 km wide, and the adjacent Central belt is a 10-km-wide zone of fault slices of ultramafic, mafic, and sedimentary rocks too complex to show in Figure 6, but illustrated schematically in Figure 9. East of Challenge (Fig. 6), areas where mafic and ultramafic rocks are structurally interleaved are shown as unit M; areas that are primarily chert-argillite and associated sedimentary rocks are shown as CA. The Yuba Rivers pluton truncates the faults in this 10-km-wide zone (Hietanen, 1976; Murphy 1984; C. Eddy, unpub. data), and subsequent deformation affected the pluton itself. The intrusive relationship of YRP has been omitted from Figure 9 for the sake of clarity.

A second apparently throughgoing fault zone, the Dogwood Peak fault (Fig. 6), bounds the eastern side of the Slate Creek complex south of the South Feather River. The fault separates volcanic rocks (SCv) from chert-argillite (CA) to the east. The effects of deformation associated with this fault extend at least 2 km westward into the volcanic rocks. The fault continues north of the Middle Fork of the Feather River (Hietanen, 1973, 1981), but it is not yet clear how far south it extends. At Goodyears Bar (Fig. 6) on the North Yuba River, intensely foliated metavolcanic rocks, possibly equivalent to the Slate Creek volcanic unit, are in fault contact with serpentinite and multiply deformed metasediments of the Feather River peridotite belt. As shown in Figure 6, the Dogwood Peak and Gillis Hill faults may intersect the faults that bound the Feather River peridotite belt near Goodyears Bar.

Our work suggests that the Slate Creek complex is the east limb of a major antiform, the core of which is occupied by the Cascade pluton (CP in Figs. 6 and 9). This interpretation is based on the repetition of similar stratigraphic and structural features on the east and west sides of the Cascade pluton. East of the pluton, the western part of the Slate Creek complex is upright and dips steeply east. It is underlain by the Camel Peak fault and by small exposures of highly deformed metasedimentary rocks (CA) that, in places, separate the lowermost, ultramafic unit (SCu) from the pluton. The area west of the Cascade pluton and south of the South Fork of the Feather River contains a similar, but oppositely facing sequence. The undifferentiated mafic rocks (M) on the southwest flank of the Cascade pluton form an ophiolitic, pseudostratigraphic sequence similar to the Slate Creek complex, but too small to illustrate at the scale of Figure 6. Murphy (1984) re-examined this area, originally mapped by Hietanen (1976, 1981) and showed that the pseudostratigraphic sequence dips steeply west and consists of, from east to west: sheared serpentinite matrix mélange; a plutonic unit containing amphibolite, layered and massive gabbro, diorite, and, at the top, diabase; and a volcanic unit containing volcaniclastic strata and massive, brecciated, and pillowed flows. Underlying and east of the serpentinite matrix mélange, there are highly deformed metasedimentary rocks (CA) that are mylonites in places. These rocks can be traced around the south end of the Cascade pluton and into the rocks underlying the Slate Creek complex. In a west-to-east traverse along the North Yuba River, sedimentary rocks change facing direction from west to east across the inferred hinge of the antiform. The origin of the mylonites and their relationship to the development of the major structures have not yet been studied, but they mark a shear zone extending at least 20 km along the southwest side of the Cascade pluton. Together with the serpentinite matrix mélange, the mylonites may reflect an important fault similar in style and structural position to the Camel Peak fault on the east side of the Cascade pluton.

Our interpretation of the northern Central belt along line E-F-G is summarized schematically in Figure 9. The dominant feature is the large antiform suggested by the repetition of pseudostratigraphy—SC units correlated with (M) undifferentiated mafic rocks—faults, and underlying metasedimentary rocks (CA) across the Cascade pluton (CP in Fig. 9). Tectonic slices of undifferentiated mafic rocks (M) and chert-argillite (CA) west of the antiform and adjacent to the Smartville complex are interpreted as higher-level thrust slices. East of the major antiform, we interpret the exposure of chert-argillite (CA) along line E-F-G as the core of a tight

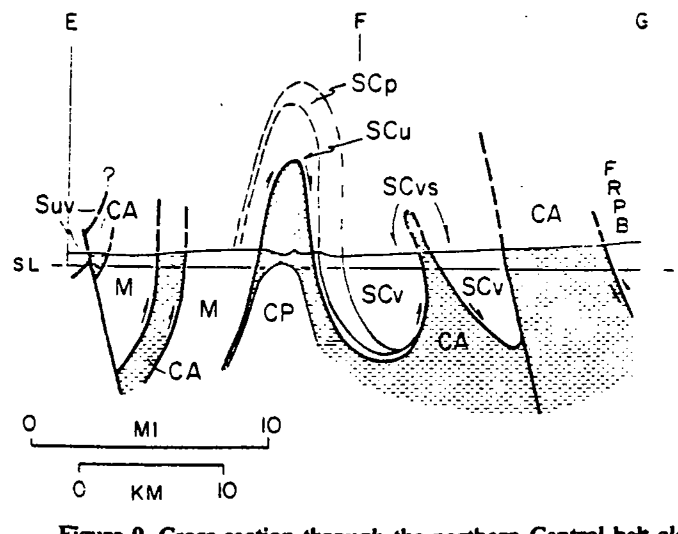

Figure 9. Cross section through the northern Central belt along line E-F-G (Fig. 6). Sea level (S.L.) and the topographic surface are indicated. No vertical exaggeration. Units as in Figures 2 and 6.

TABLE 2. MAP UNITS IN THE EASTERN BELT

Unit	Unit name	Description
Ej	Mount Jura, Milton	Jurassic (Hauterivian-Callovian) andesitic-dacitic flows, intrusives, volcaniclastics, and interbedded sediments
Ept	Arlington, Goodhue, Reeve	Permo-Triassic andesitic volcaniclastics and intrusives, basalt flows and minor limestone
Ed	Peale	Upper Mississippian to Lower Pennsylvanian Mn-Fe-rich chert, shale, breccia
	Taylor	Upper Devonian to Lower Mississippian andesite flows and clastic sedimentary rocks
	Elwell	Upper Devonian black phosphatic chert
	Sierra Buttes	Devonian intrusive and extrusive metadacite, meta-andesite, and associated volcaniclastic
Esf	Shoo Fly	Ordovician(?)-Devonian(?) quartz-rich sedimentary rocks, shale matrix "melange" containing serpentinite, limestone, tuffaceous phyllite, and chert
Ei	Intrusive rocks	Pre-Jurassic granitic plutons

possibly faulted, west-vergent antiform in the overthrust Slate Creek complex and its underlying chert-argillite basement (Edelman and others, 1983). The wide synform in the western part of the Slate Creek complex is suggested by the outcrop pattern of the ultramafic unit (SCu) between the North and Middle Yuba Rivers, where it can be traced around the hinge of the proposed synform. The Dogwood Peak fault, bounding the Slate Creek complex on the east, is interpreted as a late, F-4(?), high-angle reverse fault. This interpretation is consistent with our earlier suggestion that the Dogwood Peak fault may eventually be shown to connect with the Gillis Hill fault near Goodyears Bar.

There are several similarities in our interpretations of the northern Central belt and the Grass Valley–Colfax area. In both areas, the earliest recognizable structures are east-directed thrust faults that separate ophiolitic pseudostratigraphic complexes from underlying chert-argillite (CA). In both areas, the latest structures appear to be high-angle reverse faults that were west-directed and associated tight folds that are overturned to the west. There is evidence in the cross sections of both areas that the west margin of the Smartville complex is a zone of imbricate faults that may be thrust faults. Despite these similarities, mapping is not yet sufficiently complete to understand in detail how the major structures of the two areas might be related.

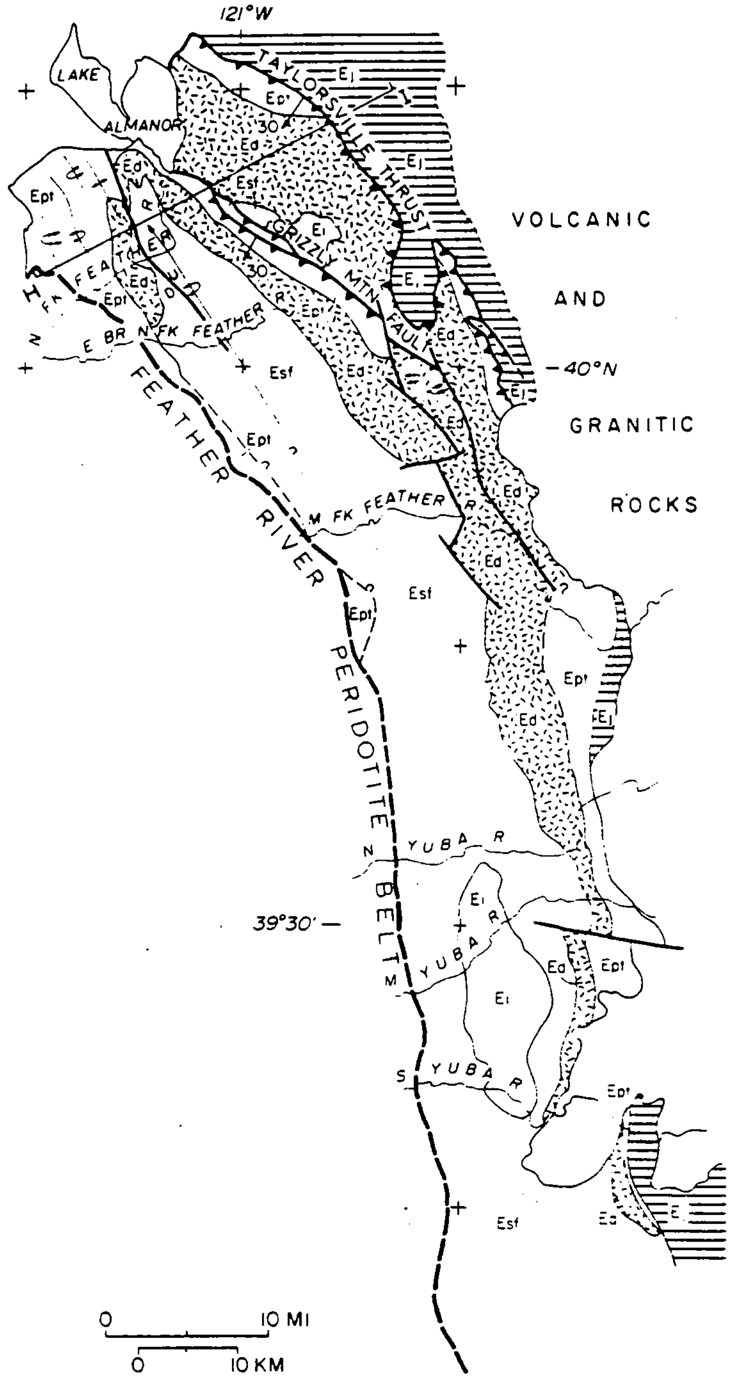

Figure 10. Sketch map of the Eastern belt. Units are listed in Table 2. The horizontal-line pattern indicates Jurassic rocks (Ej) at the base of the thrust pile; the random hachure pattern shows the Devonian units in the Eastern belt (Ed).

EASTERN BELT

Compared to the Central belt, the stratigraphy and history of the Eastern belt is well known. It is bounded on the west by the Feather River peridotite and on the east by granitic rocks of the Sierra Nevada batholith (Figs. 10, 11). The stratigraphy of the Eastern belt (Table 2) consists of metamorphosed lower Paleozoic quartz sandstone and associated slate, carbonate, and serpentinite of the Shoo Fly Complex (Esf in Figs. 10, 11), overlain by three volcanic-arc complexes of Devonian-Mississippian, Permo-Triassic, and Jurassic age (respectively, Ed, Ept, and Ej in Fig. 10). McMath (1966), D'Allura and others (1977), Schweickert and Snyder (1981), Varga and Moores (1981), Harwood (1983), and Hannah (1980) provided detailed discussions of these rocks and their paleogeographic significance. The Jurassic rocks form part of an extensive terrane of Triassic-Jurassic calc-alkaline rocks, extending hundreds of kilometres along the east side of the Sierra Nevada and Klamath Mountains, that constitutes the principal evidence for an Andean margin along the western margin of the United States during early Mesozoic time (Burchfiel and Davis, 1975; Moores, 1970; Schweickert, 1978). Many workers have emphasized that this volcanic-arc terrane is in part coeval with the Smartville complex and related rocks to the west.

The northern part of the Eastern belt contains two northeast-directed thrust faults (Figs. 10, 11). The Taylorsville fault is well documented

(McMath, 1966; Bond and others, 1977) and separates Paleozoic rocks in the upper plate from Jurassic rocks in the lower plate. The Grizzly Mountain fault is more controversial. It separates two Paleozoic sections that differ in stratigraphic detail, degree of deformation, and grade of metamorphism (Bond and others, 1977; Hannah, 1980; D'Allura, 1977). East of the fault, there occurs a thick Devonian section of volcanic rocks, the strata are folded but not appreciably foliated, and only very low-grade pumpellyite-bearing assemblages are found in the volcanic rocks. West of the fault, the Devonian section is much thinner, the rocks contain pronounced flattening foliation, and higher-grade actinolite-bearing assemblages are found. The higher grade of metamorphism suggests that the rocks west of the fault were more deeply buried than were those to the east. This fact indicates that the Grizzly fault is a thrust fault, contrary to the small apparently normal offset shown in Figure 11. Substantial movement is implied by the appreciable stratigraphic and structural differences.

Folds associated with the thrust faults are overturned toward the northeast. These northeast-verging structures pass to the west into southwest-verging ones. This structural change is expressed in the cross section (Fig. 11) as the fanlike arrangement of fold axial surfaces (Moores and Wise, 1970; Robinson, 1975; Bond and others, 1977; D'Allura and others, 1977). The presence of mesoscopic and macroscopic folds that fold the foliation in this area suggests that the fanlike arrangement of axial surfaces results from at least two periods of folding.

The simplest interpretation of these data is that folds overturned to the northeast formed during a Jurassic or younger episode of northeast-directed thrusting. These structures were later refolded, so that axial surfaces now dip east near the Feather River peridotite. Permo-Triassic rocks (Ept in Fig. 10) are involved in these west-vergent folds, so that the later deformation is Permo-Triassic or younger. The evidence we presented above favors the interpretation that both the east-vergent and west-vergent deformations are Jurassic or younger.

In the southern portion of Figure 10, the Devonian and younger rocks are present chiefly as an upright, east-dipping sequence. Whether the complex tight folding, found farther north near section line H-I (Figs. 10, 11), continues southward within the Shoo Fly (Esf) rocks is a question the answer to which must await further mapping. Schweickert (1981) proposed that the east-dipping Paleozoic-Mesozoic sequence of rocks south of the Middle Feather form the west limb of the "Sierra Nevada synclinorium," a large synformal fold formed in early Late Jurassic time.

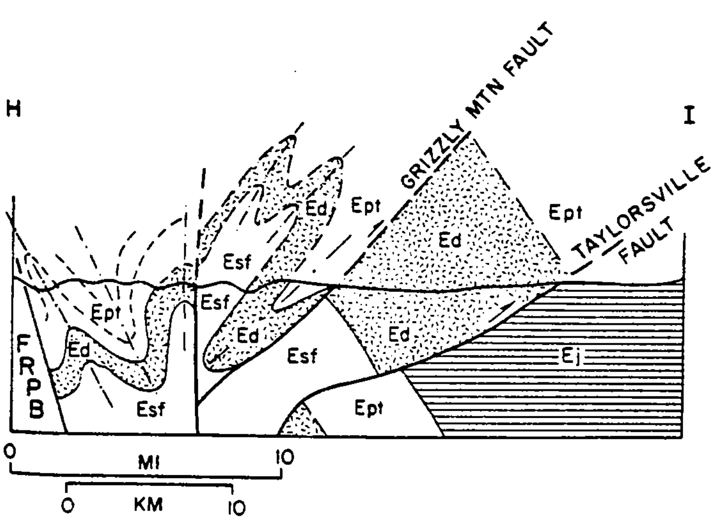

Figure 11. Cross section through the northern Eastern belt along line H–I (Fig. 10). No vertical exaggeration. Patterns and units as in Figure 10.

FEATHER RIVER PERIDOTITE BELT

The Feather River peridotite belt extends southward for ~150 km from the north end of the Sierra Nevada. Unfortunately, it is largely unmapped, and we are unable to offer an assessment of its structural evolution. As is discussed below, however, our working hypothesis for the structure of the other belts implies a complex history for the peridotite belt that must be tested by future work.

The northern part of the Feather River peridotite belt is best known. Tectonite peridotite and serpentinite are the most abundant rocks in the north, although metagabbro and amphibolite are found in some places (Ehrenberg, 1975; Standlee, 1978; Weisenberg, 1979; Hietanen, 1981). Available radiometric ages range from 387 m.y. ($Ar^{40}/39$, hornblende from a dike) to 236 m.y. ($Ar^{40}/39$, hornblende from amphibolite) and suggest a complex Paleozoic history of igneous activity and metamorphism (Weisenberg and Avé Lallemant, 1977; Standlee, 1978; Saleeby and Moores, 1979). Farther south, near the North Yuba River, the belt contains multiply deformed schist, fine-grained quartzite, and fissile slate intercalated with serpentinite and associated with mafic rocks. The metasedimentary rocks contain lawsonite, blue amphibole, and pumpellyite (Schweickert and others, 1980; Hietanen, 1981). K-Ar ages on the blueschists are as young as 174 m.y. (Schweickert and others, 1980).

Both the east and west contacts of the Feather River peridotite belt are faults. The western contact of the peridotite in the north (Hietanen, 1973; Ehrenberg, 1975) appears to be nearly vertical and is marked commonly by sheared serpentinite. Chert-argillite in the Central belt is highly deformed at this contact, and fault slices of garnet amphibolite and garnet schist occur sporadically along the contact. The eastern contact of the peridotite belt is also a fault and appears to dip steeply east (Cady, 1975).

At least some of the deformation in the Feather River peridotite belt is Jurassic. The peridotite exhibits an early northeast-striking foliation in olivine and spinel, modified by a northwest-striking foliation that is, locally, associated with tremolite overgrown by anthophyllite (Avé Lallemant and others, 1977; Ehrenberg, 1975). The northwest-striking foliation is coplanar with the faults bounding the Feather River belt and with Jurassic foliations in the Central and Eastern belts. Some of the metamorphism and deformation of the peridotite thus may be Jurassic. The K-Ar ages on the blueschists (Schweickert and others, 1980) are consistent with metamorphism (resetting or cooling) about 174 m.y. ago (Middle Jurassic).

SUMMARY AND DISCUSSION

Figure 12 is a diagrammatic summary of stratigraphic and structural relations in the northern Sierra. Our structural interpretation, based on Figures 3, 9, and 11, is summarized more completely in the composite cross section in Figure 13. From east to west, progressively older rocks are involved in the Late Jurassic Nevadan deformation. In the west, 160-m.y.-old ophiolite pseudostratigraphic assemblages are thrust (F-1) eastward over each other and over Jurassic sedimentary rocks. In the Eastern belt, Paleozoic rocks are thrust over Jurassic and Paleozoic rocks. High-angle reverse faults (F4) truncate the F1 thrust faults and are interpreted to be coeval with the 150-m.y.-old Yuba Rivers pluton (YRP in Fig. 12). We suggest that blueschist in the Feather River peridotite belt was metamorphosed about 174 m.y. ago, and that it may have been thrust under the Paleozoic peridotite and associated rocks.

Both early east-directed structures and later west-directed structures are evident in the cross section (Fig. 13). The east-directed structures are most obvious in the Eastern belt, where east-vergent folds and thrust faults that involve Jurassic rocks are present. In the northern Central belt, we

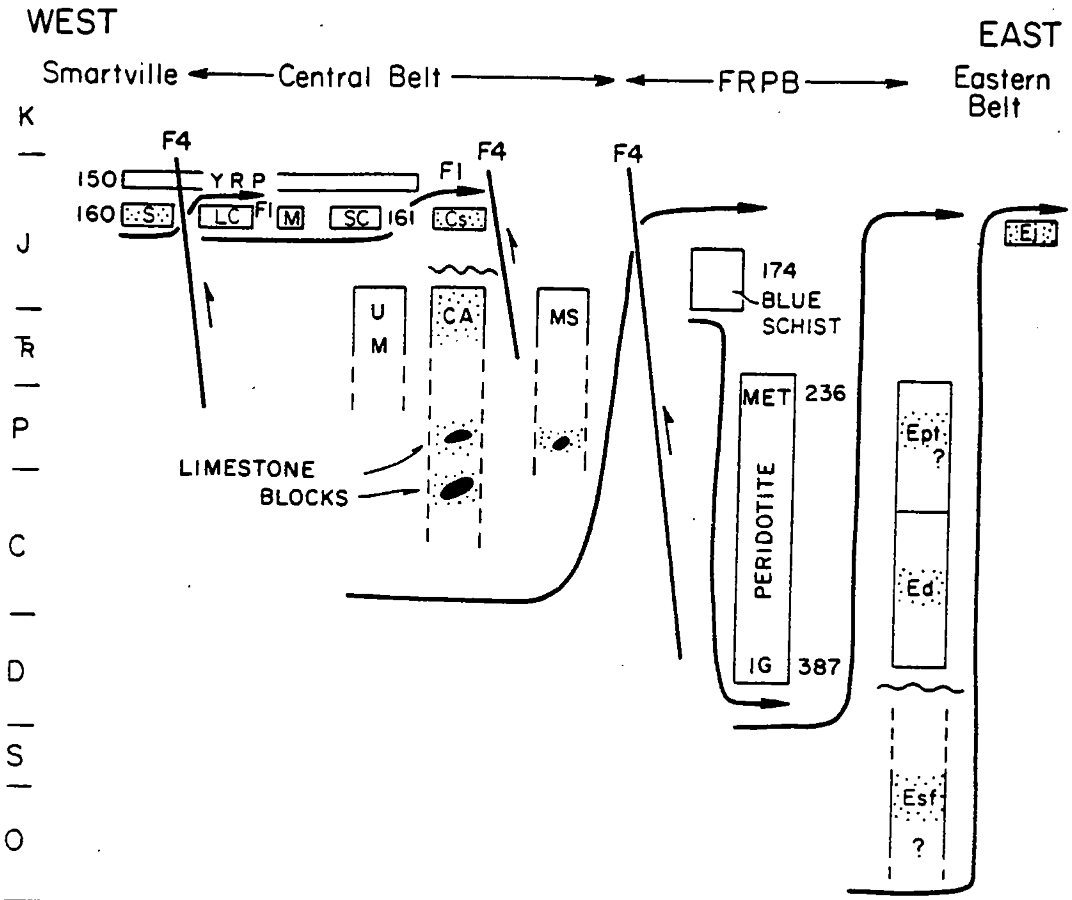

Figure 12. Diagrammatic summary of stratigraphic and structural relations in the northern Sierra Nevada. Unit abbreviations as in previous figures. Horizontal arrows represent eastward overthrusts and underthrusts. Steep lines represent high-angle reverse faults. Numbers are isotopic determinations of igneous and metamorphic events discussed in the text. The ages of stippled units are controlled, in part, by fossil evidence.

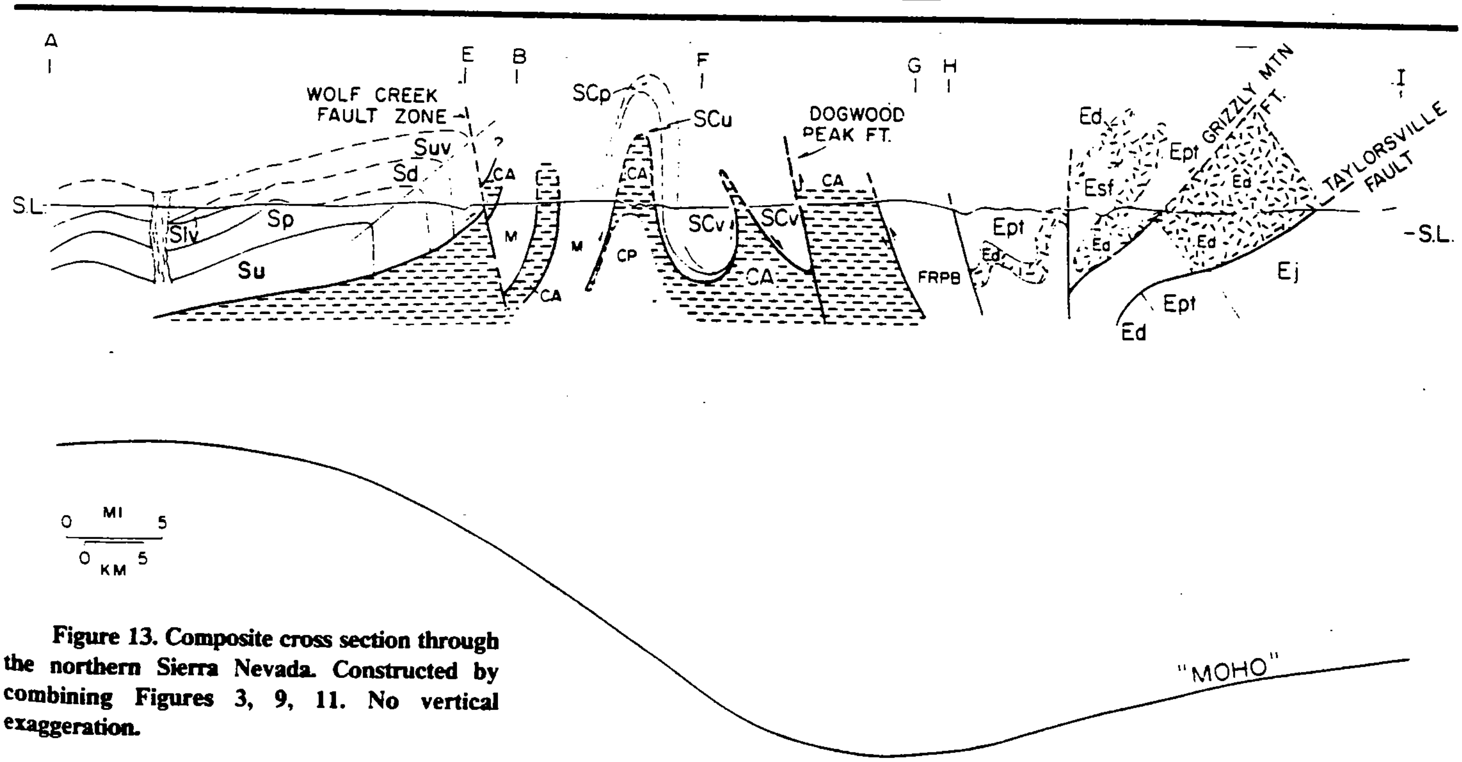

Figure 13. Composite cross section through the northern Sierra Nevada. Constructed by combining Figures 3, 9, 11. No vertical exaggeration.

interpret the Slate Creek complex and similar rocks just west of the Cascade pluton (Figs. 13, 6) as an ophiolitic, pseudostratigraphic sequence thrust over chert-argillite and subsequently folded. South of the cross section (Fig. 13), in the Grass Valley–Colfax area, thrust contacts between the ophiolitic pseudostratigraphy of the Lake Combie complex and chert-argillite have been recognized in four localities (Fig. 7). These complexes in the Central belt are very similar to the Smartville complex to the west, and, because no similar ophiolitic rocks occur to the east, we infer that thrusting occurred from west to east. Thrust faults between Smartville rocks and chert-argillite have been identified near Higgins Corner (Fig. 4) and may also occur north and west of Bloomer Hill (Figs. 2 and 5).

Steep reverse faults that dip east are the most obvious evidence of the later west-directed deformation. Overturning of folds to the west occurs (Fig. 13) east of the Feather River peridotite belt and in the eastern part of the Central belt, as well as in the Grass Valley–Colfax area (Fig. 7). Earlier folds may have been tightened and earlier faults steepened or overturned to the west during this later deformation. These west-directed structures, therefore, represent a late stage of "back folding" and "back thrusting" (*retrocharriage*) that modified the pre-existing thrust-nappe complex.

The structure of the early thrust complex is illustrated schematically in Figure 14, in which we have made the best possible attempt at our present level of understanding to remove the effects of the late deformation. Sufficient information to attempt a quantitatively precise restoration is not available. Steep, east-dipping reverse faults were removed, whereas other steep faults and geologic units were rotated clockwise to more shallow, west-dipping orientations. Folds overturned to the west were removed, and east-vergent folds were "opened" arbitrarily to remove possible tightening during the late deformation.

The principal result of this qualitative analysis is that it reveals a possible early stack of thrust sheets in the northern Sierra Nevada in which Jurassic rocks of the Eastern belt are the lowest unit now recognized, and Jurassic rocks of the Smartville complex are the highest. The extent to which the westernmost and highest units may have covered the lower, eastern thrust slices is unknown. Movement on the high-angle reverse faults (Fig. 13) or "back thrusts" is in the correct sense, however, to have exposed eastern, originally deeper levels of the overthrust terrain.

The restoration (Fig. 14) suggests that both the east and west margins of the Feather River peridotite belt dipped west and may have been east-directed thrust faults prior to their modification during the late deformation. The restoration thus implies that the peridotite was derived from the west. If, however, the rare garnet amphibolite and garnet schist that occur along the west contact of the peridotite are remnants of an earlier basal "metamorphic aureole," then either the peridotite must have been overturned to the east during the thrusting event, or it may never have dipped west. The blueschists that occur south of the line of section, near the North Yuba River, suggest that portions of an early Mesozoic subduction complex were involved in the thrusting. Clearly, our restoration and the fragmentary data imply a very complex history for the Feather River peridotite belt, but substantiation of these speculations must await detailed mapping and topical structural and petrological study.

The presence of a major overthrust belt implies not only shortening during the Late Jurassic Nevadan Orogeny, but also significant crustal thickening. Recent studies (Mavko and Thompson, 1983; Speed and Moores, 1981; Hill, 1978) suggest that the crust under the northern Sierra Nevada may be as much as 50 km thick, as shown in Figure 13. In addition, the presence of staurolite in contact aureoles of plutons in the northern Sierra (Hietanen, 1973) indicates that 10 to 20 km of crust was eroded off this region after the latest Jurassic deformation. Adding this inferred erosional component to the present crustal thickness of 50 km implies a Late Jurassic crustal thickness of 60 to 70 km. This thickness is approximately equal to that now beneath the Alps or Himalayas, despite the fact that primarily "oceanic" rocks are involved. A significant part of the observed crustal thickness may have resulted from the thrusting during the Nevadan Orogeny, as well as from later Cretaceous magmatic thickening.

Finally, how does our hypothesis apply along strike in the central and southern Sierra and in the Klamath Mountains? It is important to reconcile our observations with the dominant west-verging overthrusts and folds in the Klamath Mountains to the north and with the dominance of steep, east-dipping faults and isoclinal folds in the central and southern Sierra Nevada foothills. Indeed, new work suggests that early east-directed structures *are* found in the Klamath Mountains (Lindsley-Griffin and Griffin, 1983; Roure, 1983). Perhaps the steep faults in the southern Sierra foothills represent a more deeply eroded portion of the back-thrust system in which the postulated, early, east-vergent structures are not preserved.

CONCLUSIONS

We propose that the structure of the northern Sierra Nevada can be viewed as a stack of east-directed thrust sheets and related folds that were subsequently modified by west-directed "back thrusting" and "back folding." All of these structures appear to have formed during the Late Jurassic Nevadan Orogeny between 160 m.y. and ~150 m.y. ago.

Our interpretation depends on several key observations: (1) the presence of well-known northeast-directed thrust faults in the Eastern belt placing Paleozoic rocks over Jurassic rocks; (2) the refolding of northeast-vergent folds in the Eastern belt to produce southwest-vergent folds near the Feather River peridotite belt; (3) the recognition of relict low-angle fault contacts between the Smartville complex and chert-argillite in the Central belt; (4) the identification and correlation of three intact ophiolitic, pseudostratigraphic complexes in the Central belt that appear to have been part of the same volcanic terrane as the Smartville complex; (5) the recognition in the Central belt of early, low-angle faults separating ophiolitic complexes from underlying chert-argillite, followed by several generations of steep faults, the last of which was west-directed.

The existence of this thrust complex implies important crustal shortening and, therefore, thickening during the Nevadan Orogeny. Such shortening and thickening is an expected consequence of collisional processes invoked to explain the evolution of the Sierra (Moores, 1970; Schweickert and Cowan, 1975; Moores and Day, in press) but is less well-explained by strike-slip or transpressive models for the deformation (Saleeby, 1981).

The model we have presented for the Jurassic tectonic history of the northern Sierra Nevada is based on only a few tens of man-years of geologic mapping during the twentieth century, in an area comparable in size to the New England Appalachians or the western Alps. It would be fatuous to suppose that future work will not alter the story. We thus offer this model in the spirit of a working hypothesis that is for the first time, we believe, sufficiently detailed that it may be tested.

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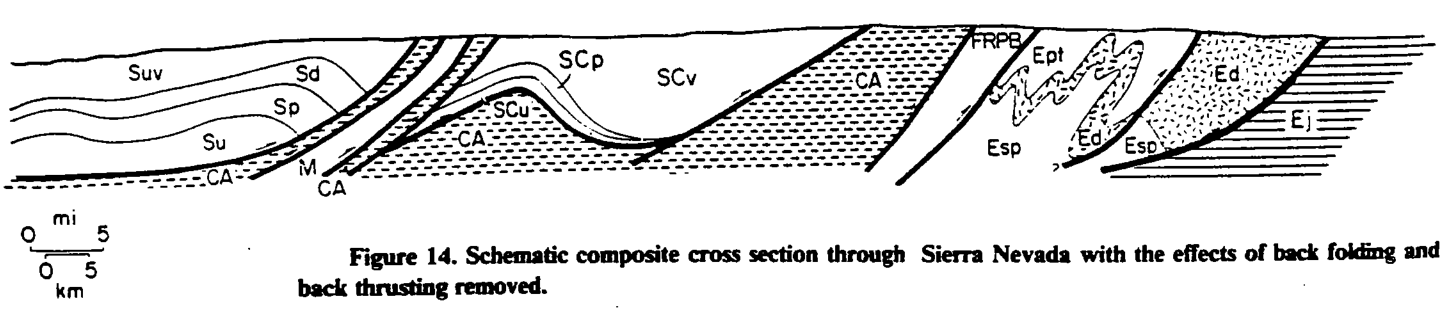

Figure 14. Schematic composite cross section through Sierra Nevada with the effects of back folding and back thrusting removed.

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