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Comparison of the Central Metamorphic Belt and Trinity terrane of the Klamath Mountains with the Feather River terrane of the Sierra Nevada

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ABSTRACT

The Central Metamorphic Belt and Trinity terrane of the Klamath Mountains and the Feather River terrane of the northern Sierra Nevada share strong similarities in their protolith types, metamorphic parageneses, structures, ages of formation and metamorphism, and relations with surrounding units. These terranes consist of ductilely deformed ultramafic to mafic plutonic and volcanic rocks and minor oceanic sedimentary rocks interpreted as oceanic lithosphere. Ultramafic rocks in the Trinity terrane and the Feather River terrane were hydrated and metasomatized under lower amphibolite-facies conditions. Mafic and sedimentary rocks in the Central Metamorphic Belt and the Feather River terrane contain upper greenschist to amphibolite-facies parageneses formed during Devonian time. Phase assemblages and mineral chemistries indicate peak *P-T* conditions of 500° to 650 ± 50°C and 500 ± 300 MPa for both terranes. The similarities imply that the Klamath Mountains and Sierra Nevada share a common early to middle Paleozoic history. The Trinity terrane/Central Metamorphic Belt represents an arc basement/subduction zone couple; the Feather River terrane may also represent such a couple.

INTRODUCTION

The Klamath Mountains and the Sierra Nevada of the North American Cordillera contain a variety of rocks that are interpreted as magmatic arcs, oceanic crust, and subduction complexes, and formed during different phases and styles of ocean/continent interaction. This chapter summarizes the results of detailed studies of the Central Metamorphic Belt and Trinity terrane of the Klamath Mountains, and the Feather River terrane of the Sierra Nevada, to illustrate the similarities and differences between early Paleozoic rocks of the Klamath Mountains and Sierra Nevada. Textural relations, determined by back-scattered electron and optical microscopy, constrain the sequence of deformational and metamorphic events. Phase relations and mineral compositions determined by electron probe microanalysis constrain the *P-T* conditions of metamorphism. Analytical techniques used in this study are discussed in Peacock and Norris (1989). Our observations, combined with those of other authors, permit correlations of the Central Metamorphic Belt and Trinity terrane of the Klamath Mountains with the Feather River terrane of the Sierra Nevada, and provide the petrogenetic framework in which to discuss the early to middle Paleozoic history of this area.

To understand the geologic relations among the Central Metamorphic Belt, the Trinity terrane, the Feather River terrane, and their surrounding units, the following section summarizes the early to middle Paleozoic rocks in both mountain belts. The descriptions of the Central Metamorphic Belt, the Trinity terrane,

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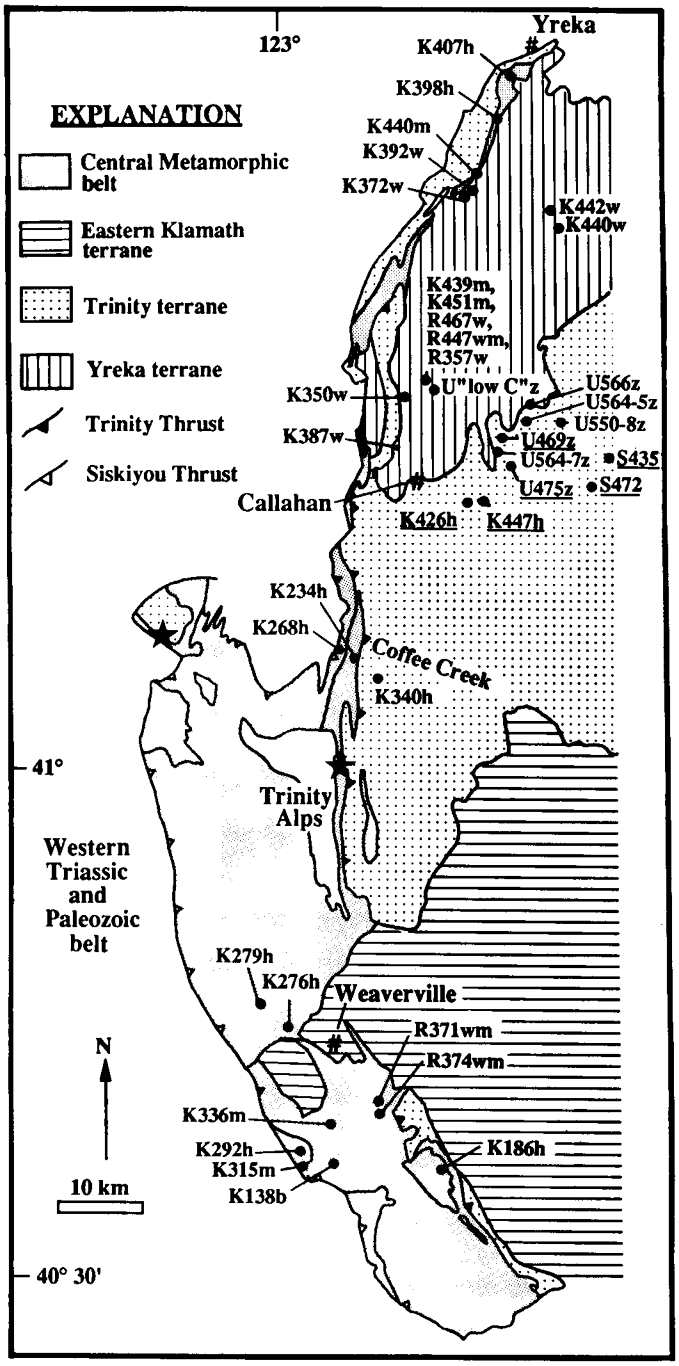

Figure 1. Geologic map of the eastern Klamath Mountains modified from Strand (1962), Davis and others (1965), Irwin (1981), Wagner and Saucedo (1987). The western Paleozoic and Triassic belt crops out west of the area shown. Radiometric abbreviations: A = Ar/Ar; K = K/Ar; R = Rb/Sr; S = Sm/Nd; U = U/Pb; m = mica; w = whole rock; h = hornblende; z = zircon (e.g., K389h indicates a 389-Ma hornblende dated by the K/Ar method. The locations of the six samples for the Sm/Nd isochron by Brouxel and Lapierre (1988) are not shown. For clarity, all age determinations of the Trinity terrane are underlined; ages that are not underlined but appear within the Trinity terrane correspond to outcrops of the Yreka terrane or Central Metamorphic Belt that are too small to show at this scale. Locations of samples used for geothermometry are indicated by stars.

and the Feather River terrane are based principally on our own observations. Radiometric ages have been recalculated as necessary, using the data of Dalrymple (1979).

KLAMATH MOUNTAINS REGIONAL GEOLOGY

The major lithostratigraphic units of the Klamath Mountains are the western Jurassic belt, the western Triassic and Paleozoic belt, the Central Metamorphic Belt, the Yreka terrane, the Trinity terrane, and the Eastern Klamath terrane (Fig. 1) (Irwin, 1960a, 1977; Silberling and others, 1987). The contacts between all units are faults (Irwin, 1960a; Lindsley-Griffin and Griffin, 1983; Renne and Scott, 1988; Schweickert and Irwin, 1989), except that the Eastern Klamath terrane may locally depositionally overlie the Trinity terrane (Brouxel and others, 1988).

Yreka terrane

The Yreka terrane consists of poorly understood, coherent, and disrupted lower Paleozoic sedimentary rocks, the more well known of which include the Duzel Phyllite and the Antelope Mountain Quartzite. The rocks form an imbricate stack of nappes in low-angle fault contact with the underlying Trinity terrane to the east and underlying unnamed amphibolite and ultramafic rocks to the west. Several of the units are inferred to have been deposited as turbidites and debris flows derived from quartzose, volcanoplutonic, and ophiolitic sources of Precambrian to Late Silurian age (Hotz, 1977; Potter and others, 1977; Lindsley-Griffin and Griffin, 1983; Wallin, 1989). Many of the sedimentary units are broken formation or melange that contain a wide variety of Early Cambrian to Early Devonian blocks, including blueschist, peridotite, and serpentinite, set in an unmetamorphosed to greenschist-facies Ordovician-Silurian sedimentary matrix. Some of these units may represent accretionary wedges (Potter and others, 1977).

Most of the sedimentary rocks in the Yreka terrane are chlorite grade or lower. Several of the units, however, contain Late Ordovician greenschist (Table 1, a and b) and Middle to Late Ordovician blueschist-facies rocks (Table 1, c and d). Near the Central Metamorphic Belt the isotopic systematics of these same units were altered, and now yield Devonian to Mississippian ages (Table 1, e and f). Moreover, these reheated rocks contain isoclinal folds that are coplanar to structures in the adjacent unnamed amphibolite and ultramafic rocks. The formation of the Yreka terrane may be related to the Trinity terrane and the Central Metamorphic Belt, as discussed later.

Trinity terrane

The Trinity terrane is an east-dipping sheet of mafic and ultramafic rocks (Davis and others, 1965; Irwin, 1966; La Fehr, 1966) overlain by thrust nappes of the Yreka terrane to the northwest and by Devonian to Jurassic rocks in the eastern Klamath terrane to the southeast, and underlain along the Trinity thrust by the Central Metamorphic Belt (Fig. 1). The Trinity terrane has been interpreted as an immature magmatic arc (Brouxel and Lapierre, 1988; Boudier and others, 1989) intruded into mid-ocean ridge–type ultramafic rocks (Jacobsen and others, 1984). The ultramafic rocks include predominantly plagioclase lherzolite, harzburgite, and dunite (Boudier and others, 1989). One sample of ultramafic rock yielded an Ordovician Sm/Nd age (Table 1, g), and a Sm/Nd isochron derived from gabbros and basalts is also Ordovician (Table 1, h). Older gabbros also yield Ordovician U/Pb ages (Table 1, i and j), whereas Silurian gabbros, diorites, and trondhjemites intrude the peridotite and older gabbros (Goullaud, 1977; Lindsley-Griffin, 1977; Quick, 1981) (Table 1, k through n). Nd isotopes indicate that the gabbros intruding the peridotite were not derived from partial melting of the peridotite, but crystallized from an isotopically distinct depleted mantle source (Jacobsen and others, 1984). It is plausible that the gabbros represent cumulate residue from arc magmas (Jacobsen and others, 1984; Brouxel and Lapierre, 1988).

Early deformation in the Trinity terrane produced isoclinal mesoscopic folds in the peridotite prior to intrusion of the later gabbros. Then, serpentine + magnetite veins formed in the peridotite synchronous with macroscopic warping (F_1 and F_2 of Goullaud, 1977). Adjacent to the Trinity thrust, the Trinity terrane was later foliated (Goullaud, 1977; Cannat and Boudier, 1985) and serpentinized by fluids derived from prograde reactions in the underlying Central Metamorphic Belt (Peacock, 1987a). The serpentinized peridotites were later folded together with the Central Metamorphic Belt (Davis and others, 1965; Goullaud, 1977).

Unnamed ultramafic rocks north of Callahan contain similar lithologies, metamorphic parageneses, structures, and ages of metamorphism (Hotz, 1977; Cashman, 1980), and in this chapter, they are considered equivalent to the Trinity terrane. However, these ultramafic rocks are not contiguous with the Trinity terrane (Hotz, 1977; Cashman, 1980) and are not in "normal" structural sequence with respect to the Yreka terrane and the amphibolite (Irwin, 1977). Ultramafic and mafic rocks of the Trinity terrane may have correlatives in the Feather River terrane of the Sierra Nevada.

Central Metamorphic Belt

The Central Metamorphic Belt consists chiefly of amphibolite structurally overlain by micaceous and feldspathic quartz

TABLE 1. ISOTOPIC AGES CITED

Yreka terrane
a. 440 ± 11 and 442 ± 12 Ma, K/Ar whole-rock (Cashman, 1980)
b. 440 ± 11 and 440 ± 13 Ma, K/Ar muscovite (Hotz, 1977; Hotz, reported in Cashman, 1980)
c. 447 ± 9 and 467 ± 45 Ma, Rb/Sr phengite–whole-rock (Cotkin and Armstrong, 1987)
d. 439 ± 13 and 451 ± 14 Ma, K/Ar white mica (Potter and others, 1981)
e. 392 ± 11, 387 ± 10, 372 ± 9, and 350 ± 10 Ma, K/Ar whole-rock (Cashman, 1980)
f. 357 ± 18 Ma, Rb/Sr whole-rock and minerals (Cotkin and Armstrong, 1987)

Trinity terrane
g. 472 ± 32 Ma, Sm/Nd plagioclase and clinopyroxene (Jacobsen and others, 1984)
h. 452 ± 40 Ma, Sm/Nd isochron on 6 samples (Brouxel and Lapierre, 1988)
i. 460 and 470 Ma, U/Pb zircon (Mattinson and Hopson, 1972a, b)
j. 475 ± 10 and 469 ± 21 Ma, U/Pb zircon (Wallin and others, 1988)
k. 418 ± 17, 426 ± 17, 439 ± 18, and 447 ± 18 Ma, K/Ar hornblende (Lanphere and others, 1968)
l. 412 Ma, U/Pb zircon (Potter and others, 1977)
m. 435 ± 21 Ma, Sm/Nd plagioclase-clinopyroxene (Jacobsen and others, 1984)
n. 412 ± 10 and 414–419 ± 15 Ma Pb/Pb zircon (Wallin and others, 1988)

Central Metamorphic Belt
o. 371 ± 11 and 374 ± 10 Ma, Rb/Sr whole-rock and mica (Lanphere and others, 1968)
p. 138 Ma, K/Ar biotite; 186 ± 10, 234 ± 30, 276, 279, 292 Ma, K/Ar hornblende; 268, 315, and 336 Ma, K/Ar muscovite (Lanphere and others, 1968)

Unnamed amphibolite west of the Yreka terrane
q. 398 ± 12 and 407 ± 12 Ma, K/Ar hornblende (Hotz, 1974)

Mule Mountain stock
r. 400 Ma, U/Pb, Pb/Pb, and K/Ar (Albers and others, 1981)

Bowman Lake batholith
s. 364–385 Ma, U/Pb zircon (Hanson and others, 1988)

Wolf Creek stock
t. 378 ± 5 Ma, U/Pb zircon (Saleeby and others, 1987)

Feather River area of Feather River terrane
u. 306–324 Ma, U/Pb zircon (Saleeby and others, 1989)
v. 241 ± 4 Ma, K/Ar hornblende (Weisenberg, 1979)

Devils Gate area of Feather River terrane
w. 248 Ma, K/Ar hornblende (Hietanen, 1981)
x. 272 ± 6 Ma, Ar/Ar hornblende (Standlee, 1978)
y. 395 ± 13 Ma, Ar/Ar hornblende (Standlee, 1978)

Yuba River area of Feather River terrane
z. 322 ± 27 and 345 ± 9 Ma, K/Ar hornblende (Böhlke and McKee, 1984)
aa. "Devonian," U/Pb zircon (Saleeby and others, 1989)
cc. 273 ± 5 Ma, K/Ar muscovite (Bohlke and McKee, 1984)
dd. 285 ± 8 Ma, K/Ar hornblende (Hietanen, 1981)

Feather River terrane
dd. ~300 Ma; Sm/Nd isochron on 4 samples (Saleeby and others, 1989)

schist and siliceous marble (Irwin, 1960b; Davis and Lipman, 1962; Davis and others, 1965). It generally crops out west of and structurally below the Trinity terrane along the Trinity thrust (Irwin, 1981). A seismic refraction study by Zucca and others (1986) suggested that the Central Metamorphic Belt extends eastward beneath the Trinity terrane for more than 100 km. The Central Metamorphic Belt overlies the Western Triassic and Paleozoic Belt along the Siskiyou thrust (Davis and others, 1965; Goodge, 1990).

Mafic rocks in the Central Metamorphic Belt are well-foliated and well-lineated amphibolite with pegmatitic, centimeter-thick quartzofeldspathic lenses (Davis and others, 1965; Hotz, 1977; Cashman, 1980; Peacock, 1985). Metamorphic recrystallization destroyed most primary igneous and sedimentary textures. Foliation is generally parallel to the Trinity thrust, and rare isoclinal fold hinges are parallel to the foliation (Davis and others, 1965; Peacock, 1985). Hornblende lineation patterns in the Central Metamorphic Belt are complex (Davis and others, 1965; Davis, 1968), but close to the Trinity thrust, lineations plunge moderately eastward.

Several observations strongly suggest that metamorphism of the Central Metamorphic Belt took place concurrent with emplacement of the Central Metamorphic Belt beneath the Trinity terrane along the Trinity thrust: (1) peak metamorphic temperatures and grain size generally increase structurally upward toward the Trinity thrust (Davis and others, 1965; Holdaway, 1965; Peacock and Norris, 1989); (2) the Trinity thrust, metamorphic foliation in the Central Metamorphic Belt, and mylonitic foliation at the base of the Trinity terrane are all subparallel (Lipman, 1964; Cannat and Boudier, 1985; Peacock, 1987a); and (3) extensive serpentinization near the base of the Trinity terrane occurred at the same time but at slightly lower temperature than the metamorphism of the underlying Central Metamorphic Belt (Peacock, 1987a). The sense of shear along the Trinity thrust, inferred from lineations and the lattice orientations of olivine and quartz crystals, is top to the west (Cannat and Boudier, 1985).

Unnamed amphibolite west of the Yreka terrane contains similar lithologies, metamorphic parageneses, and ages of metamorphism (Hotz, 1977), and in this chapter, they are considered equivalent to the Central Metamorphic Belt, as proposed by Cashman (1980). However, these rocks are not contiguous with the type Central Metamorphic Belt farther south (Hotz, 1977; Cashman, 1980), are not in "normal" structural sequence with respect to the Yreka terrane and the ultramafic sheet (Irwin, 1977), and contain slightly higher grade metamorphic mineral assemblages than the type Central Metamorphic Belt farther south (Peacock, 1985).

The oldest radiometric dates on rocks of the Central Metamorphic Belt are Middle or Late Devonian Rb/Sr whole-rock and mica isochrons (Table 1, o). Subsequent heating events affected these rocks, producing K/Ar ages ranging from 138 to 336 Ma (Table 1, p). The unnamed amphibolite west of the Yreka terrane has yielded Late Silurian to Middle Devonian K/Ar hornblende ages (Table 1, q). The Central Metamorphic Belt has probable correlatives in the Feather River terrane of the Sierra Nevada.

Eastern Klamath terrane

The eastern Klamath terrane contains more than 10 km of regionally east-dipping Devonian to Jurassic sedimentary and volcanic strata formed in an intra-oceanic arc that was active in Devonian, Permo-Triassic, and Jurassic time (Irwin, 1977; Eastoe and others, 1987; Miller, 1989). An Early Devonian basalt/rhyolite volcanoplutonic suite is represented by the Copley Greenstone, the Balaklala Rhyolite, and the Mule Mountain stock (Kinkel and others, 1956). The Balaklala Rhyolite was intruded into and erupted onto the Copley Greenstone (Albers and Bain, 1985; Lapierre and others, 1985a). The 400-Ma (Table 1, r) Mule Mountain stock is cogenetic with the Balaklala Rhyolite, and coeval with the Copley Greenstone (Barker and others, 1979; Albers and others, 1981; Lapierre and others, 1985b). REE patterns and Nd isotopes suggest that these volcanoplutonic rocks represent an immature intra-oceanic arc (Brouxel and others, 1988).

SIERRA NEVADA REGIONAL GEOLOGY

The Sierra Nevada of northern California have been divided into seven major lithostratigraphic units (Edelman and others, 1989). These are, from west to east, the Smartville, Slate Creek, Fiddle Creek, Calaveras, Red Ant, Feather River, and Northern Sierra terranes (Fig. 2). The latter five units were juxtaposed along early, low-angle, west-directed, large-displacement faults described by Edelman and others (1989), and all are separated by later, high-angle, small-displacement faults of the Foothills fault system (Clark, 1960). This chapter discusses only the Northern Sierra and Feather River terranes.

Northern Sierra terrane

The Northern Sierra terrane comprises regionally east-dipping Ordovician to Jurassic sedimentary and volcanic rocks. The Middle Ordovician to Devonian Shoo Fly Complex is the oldest unit in the Sierra Nevada, and forms the basement for magmatic arcs that were active in Devonian, mid-Permian, and Jurassic time (Harwood, 1988; Harwood and others, 1988). The Shoo Fly Complex consists of melange and structurally underlying deep-water siliciclastic rocks with minor chert, carbonate, and subaqueous tuff, and is interpreted as a west-vergent accretionary wedge thrust over a passive-margin sequence (D'Allura and others, 1977; Schweickert and others, 1984; Hannah and Moores, 1986; Saleeby and others, 1987; Girty and Guthrie, 1989).

The bulk of the Late Devonian volcanic sequence is represented by the Sierra Buttes and Taylor Formations, which consist principally of silicic to andesitic subaerial(?) and subaqueous vent complexes and flows grading to a distal submarine volcanic

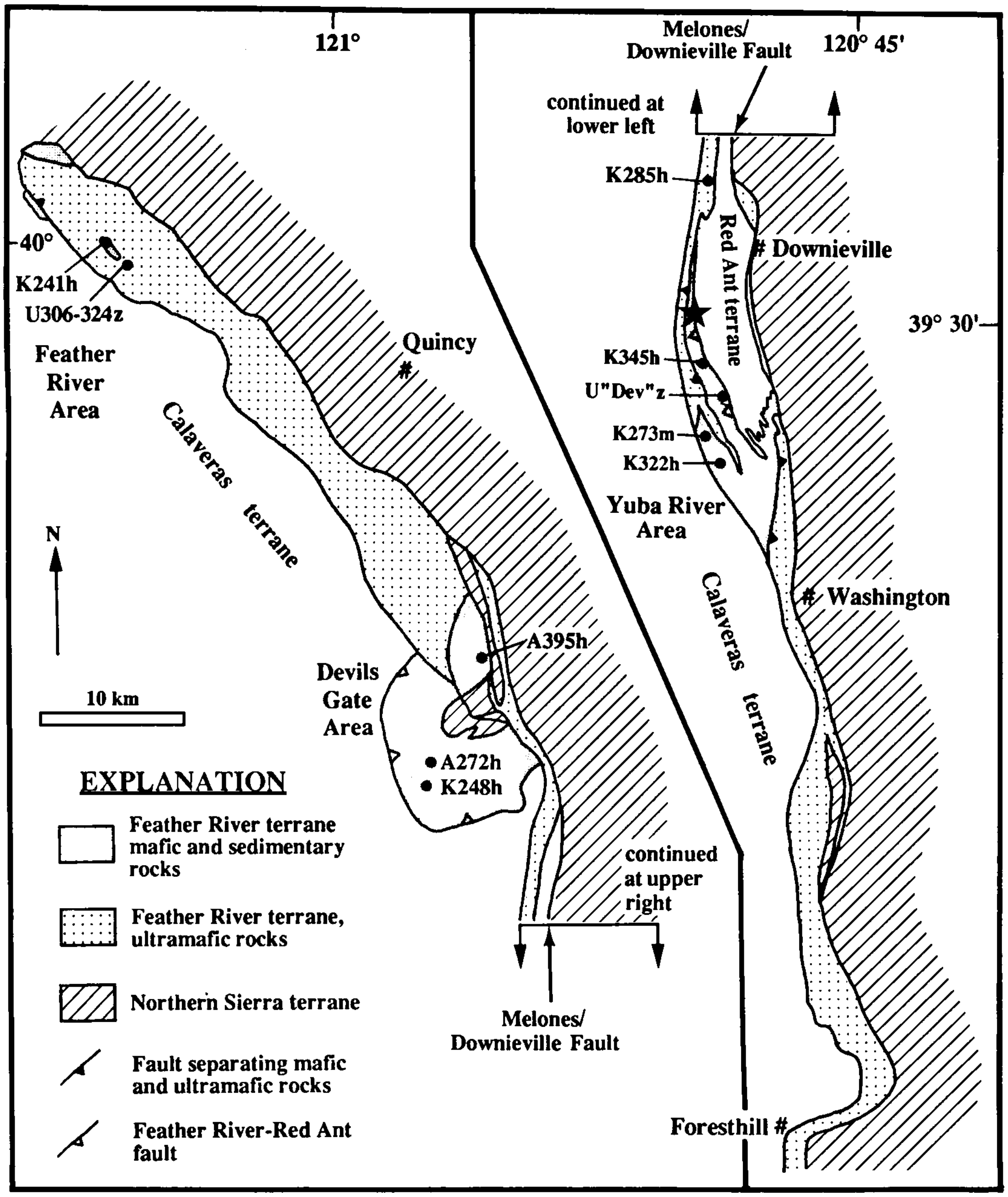

Figure 2. Geologic map of the northern (left) and southern (right) parts of the Feather River terrane and surrounding parts of the Sierra Nevada, modified from Ferguson and Gannett (1932), Lydon and others (1960), Ehrenberg (1975), Standlee (1978), Weisenberg (1979), Hietanen (1981), Edelman and others (1989), B. R. Hacker (unpublished map), and unpublished Chico Quadrangle geologic map of California. The Smartville, Slate Creek, and Fiddle Creek terranes crop out west of the area shown. Abbreviations same as in Figure 1. The locations of the five samples for the Sm/Nd isochron by Saleeby and others (1989) are not shown. Location of samples used for geothermometry are indicated by a star.

apron, also deposited unconformably on the Shoo Fly Complex (Varga and Moores, 1981; Brooks and others, 1982; Hanson and Schweickert, 1986; Hanson and others, 1988).

Several silicic intrusions, including the Middle to Late Devonian Bowman Lake batholith (Table 1, s) and the Middle Devonian Wolf Creek stock (Table 1, t) cut the Shoo Fly Complex and feed volcanic layers in the Sierra Buttes Formation (Hanson and Schweickert, 1986). Studies of trace-element (Brooks and Coles, 1980), REE (Rouer and others, 1989), and Pb isotope (Saleeby and others, 1987) abundances indicate that the Devonian to Mississippian arc comprises calc-alkaline rocks erupted through oceanic rocks.

Feather River terrane

The Feather River terrane is a heterogeneous assemblage of rocks no more than 10 km wide, but stretching for more than 150 km southward from the northern end of the Sierra Nevada. It has previously been interpreted as a partial (Moores, 1970) and complete (Edelman and others, 1989) ophiolite, although it does not represent normal mid-ocean ridge lithosphere. A broad spectrum of ages, from Devonian to Triassic, suggests that the Feather River terrane is an amalgam of rock packages whose interrelations are incompletely understood. The Feather River terrane contains all the requisite ultramafic, mafic, and sedimentary units for an ophiolite. Contacts between rock units include faults and primary igneous contacts. The Feather River terrane overlies the Red Ant and Calaveras terranes along low-angle, west-directed thrust faults, and is in contact with the northern Sierra terrane principally along the high-angle Downieville fault (Edelman and others, 1989). Much of the Feather River terrane remains unexplored, but three regions have been investigated in some detail: the Feather River area (studied by Hietanen, 1973, 1981; Ehrenberg, 1975; Weisenberg, 1979), the Devils Gate area (Standlee, 1978; Hietanen, 1981; Edelman and others, 1989), and the Yuba River area (Ferguson and Gannett, 1932; this study) (Fig. 2).

Ultramafic rocks are dominant in the Feather River terrane, and include chiefly dunite, harzburgite, and lherzolite. Primary phases of the peridotite are replaced by tremolite, chlorite, serpentine, and talc. In the large body of ultramafic rocks in the Feather River area, metamorphic minerals are abundant near faults, whereas alteration of the peridotite is nearly pervasive in the smaller ultramafic bodies in the Devils Gate and Yuba River areas. The metamorphic minerals locally define a northwest-striking foliation that is subparallel to the faults bounding the terrane, and subparallel to the foliation in the mafic rocks. This metamorphic foliation overprints and is discordant to chromite, spinel, and pyroxene layers, which strike ENE to NNE and dip steeply east and west in all three areas (Standlee, 1978; Hietanen, 1981; Edelman and others, 1989; this study).

Bodies of hornblende schist, micaceous and feldspathic quartz schists, and quartzite, ranging in size from square meters to tens of square kilometers, crop out in the Feather River terrane in all three areas; they are most abundant in the Devils Gate and Yuba River areas (Fig. 2). The quartzite occurs in ubiquitous, but volumetrically minor, isolated lenses approximately 1 m in length and 10 to 30 cm thick, and may be metamorphosed chert (Ehrenberg, 1975; Standlee, 1978; this study). The micaceous and feldspathic schists are also minor constituents with protoliths that range from arkosic to calcareous arenite. Garnet-bearing schist was mapped by Ferguson and Gannett (1932) as granite and aplite, but rare, partially unrecrystallized layers with detrital textures indicate that the protolith was sedimentary. Abundant almandine suggests that some sedimentary protoliths were ferruginous.

Hornblende schist is the most common nonultramafic rock. Igneous features such as centimeter-scale compositional layering, dikes, and pillowed flows, as well as pegmatitic, ophitic, and porphyritic textures, are sporadically preserved. Plutonic rocks range from massive to pegmatitic biotite-hornblende tonalite to massive and layered hornblende gabbro, pyroxene gabbro, hornblendite, hornblende clinopyroxenite, and clinopyroxenite. Chlorite pseudomorphs are interpreted to indicate that orthopyroxene too was once present (Hietanen, 1981; this study). P, Ti, Y, and Zr concentrations indicate that the rocks are compositionally tholeiitic basalts (Hietanen, 1981).

Locally, mafic rocks grade into ultramafic rocks (Ferguson and Gannett, 1932; Standlee, 1978; Hietanen, 1981), and many porphyritic diabase dikes cut the mafic and ultramafic rocks (Ehrenberg, 1975; Standlee, 1978; Hietanen, 1981; this study). Some dikes have chilled margins, indicating that intrusion occurred when the host rocks were relatively cool.

Foliation within the mafic and sedimentary rocks strikes NNW, dips steeply east and west, and is strongly disrupted by boudins, folds, and faults. Hornblende lineations plunge at moderate to shallow angles NNW and SSE. The folds are open to isoclinal, with amplitudes and wavelengths of millimeters to meters. Fold hinge surfaces and axes are subparallel to the foliation and lineation, respectively (Ehrenberg, 1975; Weisenberg, 1979; this study).

Feather River area. Most of the Feather River terrane in the Feather River area is altered peridotite, but there are three small exposures of mafic rocks (Fig. 2). The northern mafic body is greenschist-facies layered gabbro that grades into the ultramafic rocks. The western mafic body consists of epidote-amphibolite-facies mafic rocks, pelitic rocks, and chert. It contains a foliation that is parallel to the foliation in the structurally overlying peridotite (Ehrenberg, 1975; Weisenberg, 1979). A several-hundred-meter-wide body of amphibolite-facies mafic rock also crops out within the ultramafic rocks; zircons from interlayered plagiogranite yield a Carboniferous U/Pb age (Table 1, u), and hornblendes yield a Triassic K/Ar age (Table 1, v). The plagiogranite intrudes the ultramafic rocks (Saleeby and others, 1989), and provides a minimum age for the ultramafic rocks.

Devils Gate area. Massive gabbro, sheeted dikes, and pillowed flow rocks crop out in the Devils Gate area in the shape of a dome, with volcanic rocks near the perimeter of the mafic body and gabbro near the center (Edelman and others, 1989). Hornblende from the sheeted dikes yields Permian K/Ar and Ar/Ar ages (Table 1, w and x). Low-angle faults separate the mafic rocks from the underlying Calaveras and Red Ant terranes and from the overlying Northern Sierra terrane. The ultramafic body stretching southward from the Feather River area is separated from the Devils Gate mafic rocks by a fault. A fault also separates the Devils Gate mafic rocks from a sliver of chiefly ultramafic rock that continues south into the Yuba River area. This ultramafic sliver contains mafic and ultramafic cumulate rocks intruded by porphyritic diabase dikes with chilled margins. Hornblende from one dike yielded an Early to Middle Devonian Ar/Ar age (Table 1, y). Dikes, gabbros, and pyroxenite from the Devils Gate area contain Sm and Nd isotopic similarities with the plagiogranite in the Feather River area, and all are ~300 m.y. old (Saleeby and others, 1989).

Yuba River area. The Feather River terrane in the Yuba River area contains dunite, harzburgite, and pyroxenite that are mostly serpentinized, and amphibolite-facies layered gabbro, massive gabbro, and volcanic rocks ("Alleghany amphibolite" of Saleeby and others, 1989). The mafic igneous rocks yielded two Carboniferous K/Ar hornblende ages (Table 1, z), and are intruded by the Devonian Oriental Mine granite, which is pre- or syn-amphibolite-facies metamorphism (Coveney, 1981) (Table 1, aa). A Permian K/Ar age was obtained on white mica in a nearby micaceous schist (Table 1, bb). Hornblende from a small gabbro body yielded a Permian K/Ar age (Table 1, cc). Ultramafic rocks are gradational with the mafic rocks (Ferguson and Gannett, 1932), indicating that the ultramafic rocks are also pre-Devonian.

Age summary. The age data indicate that Carboniferous mafic rocks and pre-Carboniferous ultramafic rocks occur in the Feather River area. Metamorphism of the mafic rocks may have been Triassic. The Devils Gate area contains Carboniferous mafic rocks, probably metamorphosed in Permian time. The sliver of chiefly ultramafic rocks between the Devils Gate and Yuba River areas is pre-Devonian. Mafic and ultramafic rocks in the Yuba River area crystallized and were metamorphosed in Devonian time. Permian metamorphic ages are also recorded in the Yuba River area. The K/Ar ages are of questionable value for interpreting the ages of metamorphism because many of these amphiboles contain core and rim compositions that are radically different, but Ar/Ar and U/Pb ages indicate that crystallization of mafic igneous rocks in the Feather River terrane spanned Devonian to Carboniferous time.

PETROLOGY AND MINERAL CHEMISTRY

Ultramafic rocks

The primary minerals in ultramafic rocks of the Trinity and Feather River terranes are olivine, enstatite, Cr-diopside, and spinel (Table 2); the Trinity terrane also contains plagioclase. The compositions of olivine, enstatite, and Cr-diopside in both terranes are compared in Table 3. There are few differences, and the minerals of both terranes are similar in composition to primary minerals in most Alpine-type ultramafic bodies. Enstatite in the Feather River terrane is more aluminous, and some Cr-diopside in the Trinity terrane contains more chromium.

The anhydrous primary minerals in the ultramafic rocks are replaced by metamorphic serpentine, carbonate, chlorite, diopside, talc, tremolite, andradite, hornblende, and magnetite (Table 4). Alteration is locally extensive, obliterating all primary minerals and textures. Antigorite, lizardite, and chrysotile have been identified in both terranes. Lizardite is widespread, chrysotile occurs dominantly in veins, and antigorite in the Trinity terrane is generally restricted to exposures within 1 to 2 km of the Trinity thrust (Peacock, 1987a). Carbonate minerals are common; calcite, dolomite, and magnesite have all been observed. Chlorite commonly forms coronas around chromite in the Trinity and Feather River terranes. Both terranes contain metamorphic diopside of similar composition (Table 3). In contrast to primary Cr-diopside, which contains 1 to 5 wt% Al_2O_3, metamorphic diopside contains <0.5 wt% Al_2O_3. Talc occurs throughout the Feather River and Trinity terranes between olivine grains, as rims on tremolite and enstatite crystals, and as fine-grained masses and veins in serpentinite. Tremolite is a common minor phase that is particularly abundant near the margins of ultramafic bodies in the Feather River terrane, and near the Trinity thrust in the Trinity terrane. Tremolite crystals are grown on diopside in the Feather River terrane and replaced by serpentine in the Trinity and Feather River terranes. Magnetite is ubiquitous in both terranes, and is concentrated along the centers of serpentine "channels," and as remnants of altered spinel. Andradite occurs along enstatite and Cr-diopside cleavage planes in the Feather River terrane. The minimum variance assemblages in ultramafic rocks are listed in Table 5. Ehrenberg (1975) reported anthophyllite near the North Feather River in the Sierra Nevada, but Weisenberg (1979) specifically stated that anthophyllite does not occur there. Coleman and others (1988) listed anthophyllite as a metamorphic mineral in the Trinity terrane, but the references they cited do not. Anthophyllite was not observed in the Feather River terrane or Trinity terrane in this study.

Mafic rocks

Mafic rocks of the Central Metamorphic Belt and Feather River terrane have been metamorphosed in the greenschist, albite-epidote amphibolite, and amphibolite facies. In the Central Metamorphic Belt, metamorphic grade decreases structurally downward from amphibolite facies adjacent to the Trinity thrust to greenschist facies near the Siskiyou thrust (Peacock and Norris, 1989). Metamorphic grade also varies in the Feather River terrane, but the metamorphic zonation is poorly resolved because of smaller exposures, more pronounced deformation, and later metamorphism. Representative electron microprobe analyses of silicate phases (Table 6) illustrate the variations in mineral chemistry among the different facies.

Amphibolite facies. Amphibolite-facies mafic rocks occur in the Feather River and Yuba River areas of the Feather River terrane. They occur in the Central Metamorphic Belt north of Callahan (Cashman, 1980), and are inferred to have existed in the Trinity Alps area prior to Mesozoic(?) retrogression. The minimum-variance assemblages are listed in Table 5.

Clinopyroxene, interpreted as both igneous and metamorphic in origin, is found in the Feather River and Yuba River areas of the Feather River terrane. Pink salite ($Wo_{53}En_{32}Fs_{16}$ to $Wo_{51}En_{28}Fs_{22}$) with 3.8 to 6.3 wt% Al_2O_3, rich in TiO_2 and Na_2O, and coexisting with ferro-kaersutite or ferroan pargasite is interpreted as igneous. Colorless augite and diopside ($Wo_{44}En_{35}Fs_{21}$ to $Wo_{45}En_{45}Fs_{10}$) contain 0.6 to 3.5 wt% Al_2O_3, and are interpreted as metamorphic (Hietanen, 1981; this study). Clino-

TABLE 2. REPRESENTATIVE ANALYSES OF PRIMARY MINERALS OF THE FEATHER RIVER TERRANE*

	Olivine			Enstatite			Cr-Diopside			Spinel		Diopside		Hornblende	
Sample	5A	85	85	86	86	86	7A	7A	A4	1B	5A	40	6C	40	6C
SiO_2	41.50	41.32	40.69	55.72	55.78	55.06	53.66	51.44	51.98	0.00	0.00	48.19	48.70	39.18	39.82
Al_2O_3	b.d.	b.d.	b.d.	3.78	4.62	4.44	2.37	3.83	4.70	33.86	3.34	6.18	6.26	13.92	14.43
TiO_2	b.d.	0.05	0.03	0.09	0.10	0.15	0.24	0.74	0.52	0.10	0.53	1.67	1.43	5.08	3.04
$FeO^{\dagger}$	9.44	9.03	9.30	5.52	5.42	5.27	3.54	3.01	3.84	17.01	31.90	11.91	9.10	18.25	15.27
Cr_2O_3	b.d.	0.03	0.02	0.57	0.67	0.69	0.46	0.75	0.64	34.44	57.25	b.d.	0.05	b.d.	0.17
MnO	0.17	0.13	0.13	0.11	0.15	0.13	0.13	0.21	0.13	0.22	0.65	0.22	0.15	0.20	0.20
MgO	49.35	50.41	50.16	33.65	33.18	33.00	15.98	15.69	15.83	14.93	3.08	8.92	10.21	6.87	8.83
CaO	b.d.	b.d.	b.d.	0.67	0.66	0.61	23.82	23.82	23.12	b.d.	b.d.	22.52	23.26	11.56	11.93
Na_2O	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.42	0.41	0.38	b.d.	b.d.	1.07	0.80	2.14	2.44
K_2O	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	1.95	1.39
Total	100.46	100.97	100.34	100.11	100.57	99.35	100.62	99.89	101.14	100.59	96.75	100.68	99.95	99.15	97.52
Cations	4 oxygens			6 oxygens			6 oxygens			4 oxygens		6 oxygens		23 oxygens	
Si	1.00	1.00	0.99	1.90	1.91	1.91	1.95	1.89	1.88	b.d.	b.d.	1.82	1.83	5.99	6.06
Al^{IV}	b.d.	b.d.	b.d.	0.08	0.09	0.09	0.05	0.11	0.12	0.00	0.00	0.18	0.17	2.01	1.94
Al^{VI}	n.a.	n.a.	n.a.	0.07	0.09	0.09	0.05	0.05	0.08	1.16	0.15	0.10	0.11	0.49	0.65
Ti	b.d.	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.01	0.00	0.01	0.05	0.04	0.58	0.35
Cr	b.d.	0.00	0.00	0.02	0.02	0.02	0.01	0.02	0.02	0.79	1.69	b.d.	0.00	b.d.	0.02
Fe	0.19	0.18	0.19	0.16	0.15	0.15	0.11	0.09	0.12	0.41	1.00	0.38	0.28	2.33	1.95
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.02	0.01	0.00	0.03	0.03
Mg	1.77	1.82	1.82	1.71	1.69	1.70	0.87	0.86	0.85	0.65	0.17	0.50	0.57	1.56	2.01
Ca	b.d.	b.d.	b.d.	0.03	0.02	0.02	0.93	0.94	0.90	b.d.	b.d.	0.91	0.94	1.89	1.95
Na	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.03	0.03	0.03	b.d.	b.d.	0.08	0.06	0.53	0.67
K	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.38	0.27

*See Quick (1981) and Peacock (1987a) for analyses of similar minerals of the Trinity terrane. b.d. = below detection.

TABLE 3. COMPOSITIONS OF MINERALS IN ULTRAMAFIC ROCKS OF THE TRINITY AND FEATHER RIVER TERRANES

	Trinity Terrane	Feather River Terrane
Primary olivine	Fo_{88-93}	Fo_{88-92}
Primary enstatite	$Wo_{01}En_{91}Fs_{08}$ to $Wo_{04}En_{87}Fs_{09}$ <3.5 wt.% Al_2O_3	$Wo_{01}En_{91}Fs_{08}$ to $Wo_{02}En_{90}Fs_{08}$ >3.5 wt.% Al_2O_3
Primary Cr-diopside	$Wo_{41}En_{51}Fs_{05}$ to $Wo_{48}En_{49}Fs_{03}$ ≤1.4 wt.% Cr_2O_3	$Wo_{41}En_{54}Fs_{08}$ to $Wo_{49}En_{48}Fs_{03}$ ≤0.8 wt.% Cr_2O_3
Metamorphic Cr-diopside	$Wo_{46}En_{53}Fs_{01}$ to $Wo_{50}En_{39}Fs_{11}$	$Wo_{46}En_{53}Fs_{01}$ to $Wo_{50}En_{39}Fs_{11}$

*Trinity terrane analyses from Lindsley-Griffin (1977) and Quick (1981); Feather River terrane analyses from Ehrenberg (1975), Hietanen (1973), and this study.

pyroxene occurs only in contact aureoles in the Central Metamorphic Belt.

Ferroan pargasite and ferro-kaersutite in the Feather River and Yuba River areas of the Feather River terrane are interpreted as igneous (Table 2). Metamorphic amphiboles in both terranes are tschermakitic (Table 6). Hornblende in the Central Metamorphic Belt contains >0.75 wt% TiO_2; hornblende in quartz-bearing and quartz-absent rocks of the Feather River terrane contains 0.50 to 2.6 wt% TiO_2, and up to 5.1 wt% TiO_2, respectively.

Plagioclase is oligoclase to andesine, An_{15-36} (Ehrenberg, 1975; this study) in the Feather River terrane, and averages $\sim An_{30}$ in the highest grade Central Metamorphic Belt rocks. Garnet occurs in one mafic sample of the Feather River terrane of the Yuba River area. It ranges from $Alm_{62}Gro_{28}Pyr_{03}Spe_{01}$ to $Alm_{59}Gro_{36}Pyr_{04}Spe_{01}$ (Table 6). Two mafic samples contain garnet ranging from $Alm_{49}Gro_{26}Pyr_{18}Spe_{07}$ to $Alm_{54}Gro_{26}Pyr_{14}Spe_{03}$ in the Central Metamorphic Belt.

Albite-epidote amphibolite facies. The bulk of the Central Metamorphic Belt, small portions of the Feather River terrane in the Feather River area, and most of the Devils Gate area of the Feather River terrane, are composed of albite-epidote

TABLE 4. REPRESENTATIVE ANALYSES OF METAMORPHIC MINERALS OF THE FEATHER RIVER TERRANE*

	Diopside		Tremolite		Andradite		Serpentine		Chlorite	
Sample	5A	7A	5A	85	7A	86	85	85	85	85
SiO_2	54.65	54.27	57.45	57.26	36.56	33.77	43.81	43.39	40.70	33.78
Al_2O_3	0.54	0.03	0.80	0.68	9.53	1.52	0.21	0.25	7.02	13.82
TiO_2	0.11	0.03	0.09	0.08	4.33	0.21	0.05	0.03	0.07	0.06
FeO*	0.61	6.27	1.58	1.60	8.26	24.87	1.24	1.37	2.14	2.97
Cr_2O_3	0.25	0.04	0.52	0.39	3.69	0.51	b.d.	0.06	1.01	2.40
MnO	0.15	1.13	0.06	0.06	0.08	0.08	0.02	0.08	b.d.	b.d.
MgO	19.99	14.16	24.07	24.28	1.32	0.12	40.62	40.53	35.25	34.98
CaO	23.86	25.41	12.53	12.38	33.62	34.04	0.30	0.11	2.15	b.d.
Na_2O	b.d.	b.d.	0.29	0.26	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
K_2O	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Total	100.16	101.34	97.39	96.99	97.39	95.13	86.25	85.82	88.34	88.01
Cations	6 oxygens		23 oxygens		12 oxygens		14 oxygens		14 oxygens	
Si	1.97	2.00	7.87	7.88	2.96	2.88	4.13	4.11	3.82	3.17
Al^{IV}	0.03	0.00	0.13	0.11	0.04	0.12	0.00	0.00	0.18	0.83
Al^{VI}	0.00	0.00	0.00	0.00	0.86	0.04	0.02	0.03	0.60	0.69
Ti	0.00	0.00	0.01	0.01	0.24	0.01	0.00	0.00	0.01	0.00
Cr	0.01	0.00	0.02	0.01	0.24	0.03	b.d.	0.00	0.08	0.18
Fe	0.02	0.19	0.18	0.19	0.56	1.94	0.10	0.11	0.17	0.23
Mn	0.00	0.04	0.01	0.01	0.01	0.01	0.00	0.01	b.d.	b.d.
Mg	1.07	0.78	4.91	4.98	0.16	0.02	5.71	5.73	4.93	4.89
Ca	0.92	1.00	1.84	1.83	2.91	3.12	0.03	0.01	0.22	0.00
Na	b.d.	b.d.	0.08	0.07	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
K	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.

*See Peacock (1987a) for analyses of similar minerals from the Trinity terrane. b.d. = below detection.

TABLE 5. METAMORPHIC ASSEMBLAGES

Ultramafic Rocks
(1) Ol + Tr + Atg + Chl + Mt (Peacock, 1987a; this study)
(2) Tc + Tr + Srp + Mt (Lipman, 1964; Hietanen, 1973; Ehrenberg, 1975; this study)
(3) Di + Tr + Srp + Mt (Ehrenberg, 1975; this study)

Assemblages (1) through (3) occur in the Feather River terrane; (1) and (2) have been reported from the Trinity terrane.

Rodingites
(1) And + Di + Chl + Ido (Hietanen, 1981; this study)
(2) And + Di + Ido + Pg-Hb (this study)
(3) Gro + Ido + Zo + Tr + Cal (Hietanen, 1973)

Rodingites have been recognized only in the Feather River terrane.

Mafic Rocks
(1) Di + Hb + Olg + Bio + Ilm + Qtz (this study)
(2) Hb + Olg + Bio + Ilm + Qtz (Hietanen, 1981; Edelman and others, 1989)
(3) Sal + Hb + Ab + Gar + Spn + Qtz + Rut (Ehrenberg, 1975)
(4) Di + Hb + Olg + Ep + Ep + Chl (Holdaway, 1965; Ehrenberg, 1975)
(5) Hb + Olg + Ep + Spn + Qtz (Davis and others, 1965; Holdaway, 1965; Hietanen, 1981; Edelman and others, 1989; this study)
(6) Act + Ab + Ep + Qtz + Chl + Spn (Hotz, 1977; Standlee, 1978; Peacock, 1985; Edelman and others, 1989)
(7) Hb + Ab + Ep + Qtz + Chl + Spn (Hotz, 1977; Standlee, 1978; Cashman, 1980; Hietanen, 1981; Peacock, 1985; Edelman and others, 1989; this study)
(8) Hb + Olg + Ep + Chl + Qtz + Bio + Gar (Holdaway, 1965)
(9) Hb + Ab + Ep + Chl + Gar + Spn + Qtz (Holdaway, 1965)

Assemblages (5) through (9) are found in the Central Metamorphic Belt, and (1) through (7) in the Feather River terrane.

Metasedimentary Rocks
(1) Qtz + Olg + Gar + Mus or Bio + Chl (Ehrenberg, 1975; this study)
(2) Qtz + Ab + Gar + Tr + Ep + Cal + Spn + Chl (Peacock, 1987)
(3) Qtz + Ab + Mus + Bio + Gar + Ido + Cal + Spn (Davis and others, 1965)

Assemblage (1) occurs in the Feather River terrane, and assemblages (2) and (3) are found in the Central Metamorphic Belt.

Notes: Ab = albite; Act = actinolite; And = andradite; Atg = antigorite; Bio = biotite; Cal = calcite; Chl = chlorite; Di = diopside; Ep = epidote; Gar = garnet; Gro = grossularite; Hb = hornblende; Ido = idocrase; Ilm = ilmenite; Mt = magnetite; Mus = muscovite; Ol = olivine; Olg = oligoclase; Pg-hb = pargasitic hornblende; Qtz = quartz; Rut = rutile; Sal = salite; Spn = sphene; Srp = serpentine; Tr = tremolite; Tc = talc; Zo = zoisite.

amphibolite-facies rocks (Table 5). Hornblende typically contains 0.25 to 1.0 wt% TiO_2. Epidote is commonly zoned, with $Fe^{3+}/(Al+Fe^{3+})$ increasing from core to rim in most samples, although reverse zoning is also observed. Albite is typically $An_{01\text{-}05}$ in the Central Metamorphic Belt and $An_{01\text{-}11}$ in the Feather River terrane (Ehrenberg, 1975; this study). Several samples in the Central Metamorphic Belt contain peristerite pairs ($An_{09\text{-}12}$ and $An_{20\text{-}30}$), suggesting metamorphic conditions transitional to amphibolite facies. Chlorite, interpreted as a stable prograde phase in some samples, occurs as elongate pods oriented parallel to the foliation.

Greenschist facies. Greenschist-facies mafic rocks occur around the border zone of the Devils Gate mafic body in the Feather River terrane and in the Central Metamorphic Belt near the basal Siskiyou thrust. Local green biotite indicates upper greenschist facies (Table 5). Hornblende rims on actinolite grains suggest that at least some of the Central Metamorphic Belt greenschists were not formed by retrogression, but rather represent the highest metamorphic grade attained.

Rodingites. Gabbroic dikes and inclusions within the ultramafic rocks in the Feather River terrane are commonly altered to rodingites (Table 5). When strongly altered, the entire rock may be replaced by magnesite and talc, but more typically, the rodingites are composed of andradite alterations of plagioclase, and idocrase + diopside + chlorite intergrowths replacing pyroxene. The rodingite and host ultramafic rock are usually separated by a centimeter-scale zone of intergrown Mg-Fe-, Fe-Mg-chlorite, and magnetite. Rodingites have not been recognized in the Central Metamorphic Belt.

Later metamorphism. All the Feather River terrane rocks in the Yuba River area were metamorphosed under pumpellyite-actinolite facies conditions during Jurassic(?) time (Hacker, 1988). Many of the minerals diagnostic of this metamorphic event have been recognized throughout the Feather River terrane and Central Metamorphic Belt, but the grade of metamorphism has always been termed greenschist facies (Davis and others, 1965; Ehrenberg, 1975; Standlee, 1978; Cashman, 1980; Hietanen, 1981; Peacock and Norris, 1989). Pumpellyite was only recognized in the Yuba River area by back-scattered electron microscopy, and it may occur in the Central Metamorphic Belt and in other parts of the Feather River terrane.

Sedimentary rocks

Mineral assemblages in quartz-bearing sedimentary rocks in the Central Metamorphic Belt and Feather River terrane record garnet-zone metamorphic conditions (Table 5). Amphibole in calcareous units is actinolite or hornblende, perhaps reflecting the original Al_2O_3 content of the protolith. Garnet compositions range from $Alm_{68}Pyr_{28}Gro_{03}Spe_{01}$ to $Alm_{58}Pyr_{35}Gro_{06}Spe_{01}$ in the Feather River terrane (Table 5) and $Alm_{66}Pyr_{04}Gro_{27}Spe_{02}$ to $Alm_{50}Pyr_{10}Gro_{05}Spe_{35}$ in the Central Metamorphic Belt. Muscovite in the Feather River terrane and Central Metamorphic Belt contains 10 percent celadonite component.

TABLE 6. REPRESENTATIVE ANALYSES OF METAMORPHIC MINERALS IN MAFIC ROCKS OF THE FEATHER RIVER TERRANE*

	Hornblende					Garnet	Pyroxene			
Sample	26	105	27	6E	126	126	26	105	27	6E
SiO_2	48.47	49.58	43.22	45.49	41.75	38.27	52.27	53.84	52.41	53.34
Al_2O_3	6.96	7.95	11.48	10.68	15.32	21.61	1.23	0.74	1.45	1.27
TiO_2	1.12	1.21	1.88	2.29	1.16	0.02	0.30	0.10	0.18	0.20
FeO*	13.56	9.41	16.50	9.19	16.59	27.47	11.02	7.33	10.63	5.65
Cr_2O_3	0.04	0.22	0.12	0.15	b.d.	b.d.	b.d.	0.06	0.05	0.10
MnO	0.27	0.17	0.25	0.15	0.13	1.78	0.36	0.27	0.35	0.17
MgO	13.60	16.04	10.30	14.69	8.77	3.64	13.29	14.93	12.20	15.40
CaO	11.87	11.84	11.31	12.19	11.25	7.60	21.87	22.87	22.52	23.65
Na_2O	1.15	0.98	1.98	1.50	1.89	b.d.	0.30	0.20	0.35	0.26
K_2O	0.46	0.57	0.33	1.04	0.76	b.d.	b.d.	b.d.	b.d.	b.d.
Total	97.50	97.97	97.37	97.37	97.62	100.39	100.64	100.34	100.14	100.04
Cations	23 oxygens					12 oxygens	6 oxygens			
Si	7.05	7.01	6.41	6.60	6.19	3.01	1.96	1.99	1.97	1.97
Al^{IV}	0.95	0.99	1.59	1.40	1.81	0.00	0.04	0.01	0.03	0.03
Al^{VI}	0.24	0.33	0.42	0.42	0.86	2.00	0.01	0.02	0.04	0.02
Ti	0.12	0.13	0.21	0.25	0.13	0.00	0.01	0.00	0.01	0.01
Cr	0.00	0.02	0.01	0.02	b.d.	b.d.	b.d.	0.00	0.00	0.00
Fe	1.65	1.12	2.05	1.12	2.06	1.81	0.35	0.27	0.33	0.17
Mn	0.03	0.02	0.03	0.02	0.02	0.12	0.01	0.01	0.01	0.01
Mg	2.95	3.38	2.28	3.18	1.94	0.43	0.74	0.82	0.68	0.85
Ca	1.85	1.79	1.80	1.89	1.79	0.64	0.88	0.90	0.91	0.93
Na	0.32	0.27	0.57	0.43	0.54	b.d.	0.02	0.01	0.03	0.02
K	0.09	0.10	0.06	0.19	0.14	b.d.	b.d.	b.d.	b.d.	b.d.

*See Peacock and Norris (1989) for analyses of similar minerals from the Central Metamorphic belt. b.d. = below detection.

METAMORPHIC HISTORY

Ultramafic rocks

As a first approximation, metamorphism of ultramafic rocks can be discussed in terms of the system MgO-SiO_2-H_2O. An internally consistent set of *P-T* reaction positions for the MgO-SiO_2-H_2O system generated from the thermodynamic data of Robinson and others (1982) was presented by Peacock (1987a). Antigorite is stable to temperatures as high as 570°C for P_{H_2O} = 500 MPa. The lack of antigorite + brucite constrains the temperature to >425°C. Coexisting talc and tremolite indicate temperatures of >475°C at 500 MPa. Actual temperatures were probably slightly lower because of dilution of the fluid by CO_2 (Trommsdorff and Evans, 1977).

Four lines of evidence strongly suggest that the sources of fluid responsible for the antigorite serpentinization were dehydration reactions in the underlying Central Metamorphic Belt during thrusting: (1) the spatial restriction of antigorite to within 1 to 2 km of the Trinity thrust; (2) the presence of talc and tremolite formed by metasomatism at the Trinity thrust; (3) metamorphic δD values indicate that nonmeteoric water was involved; and (4) the foliation in the antigorite schist, the Trinity thrust, and the foliation in the Central Metamorphic Belt are all subparallel (Peacock, 1987a).

Mafic rocks

Metamorphic temperatures and pressures in the Central Metamorphic Belt and Feather River terrane can be estimated from the observed mineral assemblages, mineral chemistry, and limited thermometry of the mafic rocks. Relevant experimentally determined reactions in basaltic systems were presented by Peacock and Norris (1989). At P = 500 MPa and f_{O_2} defined by the QFM buffer, the amphibolite facies occurs at T >650°C, the albite-epidote amphibolite facies at ~500° to 650°C, and the greenschist facies at T <550°C. The presence of hornblende + calcic plagioclase in the mafic rocks indicates that metamorphic conditions locally reached the lower amphibolite facies. Locally developed hornblende + clinopyroxene assemblages in the Feather River terrane indicate peak metamorphic temperatures in the upper amphibolite facies. Maximum metamorphic temperatures close to the Trinity thrust were probably in the range of 600° to 700°C, whereas upper greenschist facies assemblages at

TABLE 7. THERMOMETRY FOR THE FEATHER RIVER TERRANE

Graham and Powell (1984)

Garnet X(Fe)	Garnet X(Mg)	Garnet X(Ca)	Garnet X(Mn)	Hornblende Fe	Hornblende Mg	T(°C)
1.9	0.42	0.55	0.12	2.02	1.94	621

Hodges and Spear (1982)

Garnet X(Fe)	Garnet X(Mg)	Garnet X(Ca)	Garnet X(Mn)	Biotite Al^{VI}	Biotite Ti	Biotite Cr	Biotite Fe	Biotite Mn	Biotite Mg	T(°C)
1.9	0.40	0.54	0.15	0.54	0.08	0.00	1.09	0.01	1.29	648

Garnet-biotite temperature calculated for 500 MPa pressure.

the base of the Central Metamorphic Belt record peak metamorphic temperatures of 450° to 550°C.

Only two samples each in the Feather River terrane and Central Metamorphic Belt were suitable for quantitative thermometry (see Fig. 2 for sample locations). Propagation of a ±2 percent uncertainty in the microprobe analyses through the thermometer equations results in an analytical uncertainty of approximately ±25°C. Calibration uncertainties are much larger, perhaps in excess of ±100°C for some geothermometers (Hodges and McKenna, 1987). Graham and Powell (1984) calibrated Fe/Mg partitioning between garnet and hornblende against the garnet-clinopyroxene geothermometer of Ellis and Green (1979). The Central Metamorphic Belt sample yields a metamorphic temperature of 640°C (Peacock and Norris, 1989), and the Feather River terrne sample yields 621°C (Table 7). Fe-Mg exchange between garnet and biotite is also temperature sensitive and has been calibrated as a geothermometer. For the Hodges and Spear (1982) calibration, garnet-biotite rim compositions yield average temperatures of 695° and 648°C, respectively, for the Central Metamorphic Belt (Peacock and Norris, 1989) and Feather River terrane samples (Table 7).

Mineral assemblages constrain metamorphic pressures to lie between approximately 200 and 900 MPa. At pressures less than ~200 MPa, albite + hornblende is unstable with respect to oligoclase + actinolite (e.g., Grapes and Graham, 1978; Liou and others, 1985). At pressures greater than ~900 MPa, mafic rocks should contain sodic amphibole (Liou and others, 1985), which is not observed in the Central Metamorphic Belt or Feather River terrane.

Amphibole chemistry can be a useful indicator of metamorphic pressure (e.g., Laird and Albee, 1981). In a comprehensive study of mafic schists from different metamorphic terranes, Laird and Albee (1981) demonstrated that the edenite and tschermakite contents of amphibole increase with increasing metamorphic grade in mafic rocks that contain a "common" mineral assemblage. Laird and Albee (1981) and Hynes (1982) presented discriminant diagrams that distinguish among amphiboles from high- and medium- to low-pressure facies series metamorphism. Amphibole compositions from the Central Metamorphic Belt and the Feather River terrane plot consistently within the moderate- to low-pressure facies series field (Fig. 3).

The rodingite assemblage andradite + diopside + chlorite + idocrase found in the Feather River terrane could have formed at temperatures of 300° to 650°C at 500 MPa in equilibrium with an H_2O-rich fluid (X_{CO_2}<0.03) (Rice, 1983).

Sedimentary rocks

Spear and Cheney (1989) calculated the maximum thermal stability of garnet + biotite + chlorite + quartz + muscovite in the system KFMASH as ~575°C at 500 MPa. Rocks with this assemblage occur in the Feather River terrane, but none was suitable for thermobarometry because of retrogression. Calc-schists in the Central Metamorphic Belt containing tremolite + calcite + quartz formed at temperatures about 550° to 600°C (Metz and Trommsdorff, 1968) and below ~650°C (Turner, 1981, p. 164) at 500 MPa, those containing diopside + quartz + tremolite formed above 600° to 650°C (Turner, 1981, p. 164). Diopside was found in one limestone block in the Feather River terrane (Ferguson and Gannett, 1932), suggesting temperatures of >600°C at pressures of 500 MPa if the diopside formed by the breakdown of quartz and dolomite (Turner, 1981, p. 164).

Summary of metamorphic P-T conditions

Based on the observed mineral assemblages, mineral chemistry, and limited thermometry, peak metamorphic temperatures in the Central Metamorphic Belt decrease from 650 ± 50°C at the Trinity thrust to 500 ± 50°C at the base of the Central Metamorphic Belt. Intercalated sedimentary rocks indicate peak metamorphic temperatures of 600 ± 50°C. Concomitant metamorphic pressures are loosely constrained as 500 ±0 MPa. Peak metamorphic temperatures and pressures for mafic rocks in the Feather River terrane were roughly 600° to 650 ± 50°C and 500 ± 300 MPa, and intercalated sedimentary rocks were metamorphosed at temperatures of 550° to 600°C. Mineral assemblages indicate that metamorphism in ultramafic rocks of the Feather River terrane and the Trinity terrane occurred at peak temperatures of 525 ± 50°C.

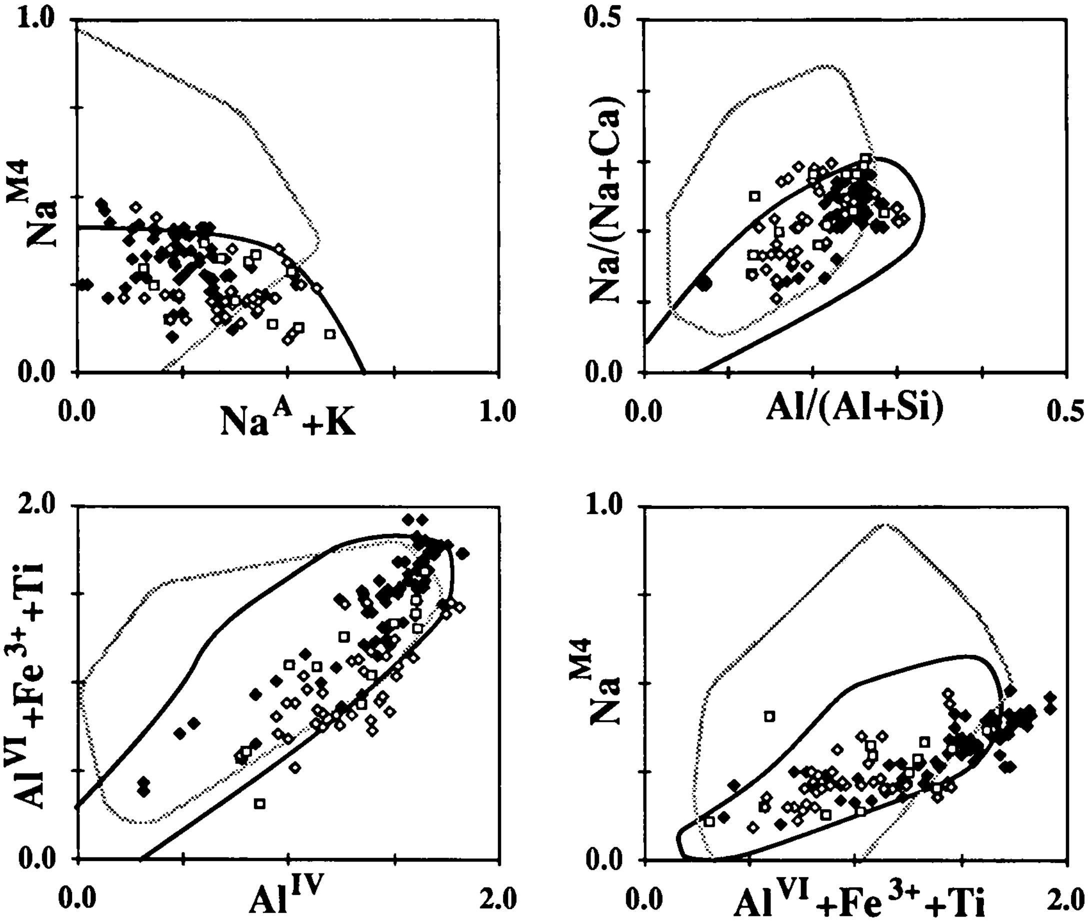

Figure 3. Amphibole analyses from the Central Metamorphic Belt (filled diamonds) and the Feather River (open squares) and Yuba River (unfilled diamonds) areas of the Feather River terrane. The field for high-pressure facies series amphiboles (pale line) is after Laird and Albee (1981, p. 140–141), and the medium- to low-pressure field (heavy line) is after Laird and Albee (1981) and Hynes (1982). The "medium-pressure" Haast schists compositions of Cooper and Lovering (1970) plotted by Laird and Albee (1981) are not shown in the figure because recent study of the Haast schists (Yardley, 1982) reveals rather different amphibole compositions than those of Cooper and Lovering, and reveals that the schists were metamorphosed under high-pressure conditions prior to medium-pressure metamorphism. Amphibole microprobe analyses were recalculated using stoichiometric constraints of Laird and Albee (1981), which generally result in maximum permissible Fe^{3+}.

DISCUSSION

Comparison of the Sierra Nevada and Klamath Mountains

The first attempt at correlations between the Sierra Nevada and Klamath Mountains was by Davis (1969), who correlated the Trinity thrust with the Melones (= Downieville) Fault in the northern Sierra Nevada. More recent correlations by Schweickert and Snyder (1981) and Sharp (1988) are discussed below. Based on the descriptions of lithologies, structures, and metamorphic parageneses in this chapter, we consider four potential correlations between the Trinity terrane and Central Metamorphic Belt of the Klamath Mountains with the Feather River terrane of the Sierra Nevada. References for data restated in this section have been cited earlier.

Feather River terrane ultramafic rocks = Trinity terrane ultramafic rocks. Ophiolitic rocks in the Klamath Mountains and Sierra Nevada have undergone multiple episodes of magmatism and metamorphism, some of which were coincident in both mountain belts. The ultramafic rocks in the Trinity terrane are Ordovician, and the dated ultramafic rocks in the Feather River terrane are pre-Carboniferous or pre-Devonian. Thus, the Trinity and Feather River terranes both contain ultramafic rocks that may be correlative. The ultramafic rocks in both mountain belts contain similar protoliths, although plagioclase lherzolite has not been recognized in the Feather River terrane. Perhaps the most compelling link is that both the Trinity and Feather River terrane ultramafic rocks were metamorphosed at ~525°C in Devonian time, and then cooled through greenschist-facies conditions. High ϵ_{Nd} initial values reported for the Trinity terrane (Jacobsen and others, 1984) have been measured in the Kings River ophiolite of the southern Sierra Nevada (Shaw and others, 1987); peridotite in the Sierra Nevada have not yet been analyzed. Metamorphism of the Trinity terrane occurred coincident with metamorphism of the Central Metamorphic Belt and movement along the Trinity thrust. Perhaps the metamorphism in the Feather River terrane occurred by similar means.

Feather River terrane mafic rocks = Trinity terrane mafic rocks. It is probable that some of the mafic igneous rocks in the Trinity and Feather River terranes are correlative. Mafic rocks of the Trinity terrane are Ordovician gabbros, dikes, and basalts, and Silurian gabbros and diorites. Some mafic rocks in the Sierra Nevada preserve igneous textures and minerals, and are gradational with the ultramafic rocks. These include the northernmost exposure of pre-Carboniferous mafic rocks in the Feather River area, the sliver of pre-Devonian ultramafic and mafic rock between the Devils Gate and Yuba River areas, and pre-Devonian mafic rocks in the Yuba River area. Pre-Devonian mafic rocks in the Kings River ophiolite of the southern Sierra Nevada are also potentially correlative with the Trinity terrane (Shaw and others, 1987).

Feather River terrane mafic and sedimentary rocks = Central Metamorphic Belt mafic and sedimentary rocks. Schweickert and Snyder (1981) suggested that the Central Metamorphic Belt is correlative with portions of the Shoo Fly Complex. Sharp (1988) suggested correlation of the Central Metamorphic Belt with mafic rocks in the Feather River terrane. Our work suggests that the Central Metamorphic Belt is correlative with mafic rocks in the Feather River terrane, and not with part of the Shoo Fly Complex. Both the Central Metamorphic Belt and the Feather River terrane in the Yuba River area were metamorphosed at greenschist to amphibolite-facies conditions in Devonian time, contain similar protolith lithologies and textures, underlie serpentinized ultramafic rocks with subparallel foliations, and overlie lower Mesozoic blueschist-facies rocks (Hacker and Goodge, this volume). The correlation would be strengthened if a systematic inverted metamorphic gradient could be demonstrated in the Feather River terrane. The most remarkable difference between the Central Metamorphic Belt and the Feather River terrane mafic rocks is that igneous activity continued during Carboniferous and Permian time in the Feather River terrane, but ceased by Devonian time in the Trinity terrane. Perhaps the late Paleozoic North Fork terrane ophiolite (Ando and others, 1983) shares affinities with the Carboniferous and Permian rocks in the Sierra Nevada.

Melones Fault = Trinity thrust. Davis's (1969) correlation of the Trinity thrust with the Melones Fault requires modification in light of our studies. The Trinity thrust separates the ultramafic rocks of the Trinity terrane from the dominantly mafic rocks of the underlying Central Metamorphic Belt. In contrast, the Melones Fault separates the melange and sedimentary allochthons of the Shoo Fly Complex from the underlying mafic/ultramafic rocks of the Feather River terrane. The more likely equivalent of the Trinity thrust in the Sierra Nevada is the unnamed contact between the ultramafic and mafic rocks within the Feather River terrane exposed in the Yuba River area.

Implications for the early to middle Paleozoic evolution of the Cordillera

These possible correlations allow more accurate reconstruction of the early to middle Paleozoic evolution of the Klamath Mountains and Sierra Nevada. In Late Proterozoic (~850 Ma; Dickinson, 1977) through Cambrian time (~650 Ma; Stewart and Suczek, 1977), rifting produced a passive margin along the western edge of the North America craton. From then until Devonian time, central Nevada was the site of an east-to-west transition from continental shelf and slope deposition adjacent to the craton, to eugeosynclinal deposition farther west (Stewart, 1980). The mafic section of the Trinity terrane formed during Ordovician time (~450 Ma).

Ages near the Ordovician/Silurian boundary (~440 Ma) for blueschist and greenschist-facies rocks in the Yreka terrane and magmatic arc plutons intruded into the Trinity terrane indicate subduction at that time. These features may be related to one intraoceanic subduction zone, but whether the subduction zone dipped east or west is not known. More plutons intruded the Trinity terrane in Late Silurian time (~415 Ma), suggesting continued subduction. Perhaps the tectonic setting was a Marianas-type intraoceanic arc, with active volcanoes built on multiply intruded basement separated from one or more remnant arcs by a back-arc basin. Inception of the Feather River terrane may have occurred in a similar environment. At this time, sediments in the Yreka terrane and the Shoo Fly Complex were derived from Precambrian cratonic and early Paleozoic volcanoplutonic sources (Girty and Wardlaw, 1984, 1985; Wallin, 1989). Sediments derived from similar sources were being deposited in central Nevada (Gilluly and Gates, 1965; Stewart, 1980; Girty and Wardlaw, 1984, 1985).

Plutonic and volcanic rocks were erupted in the eastern Klamath terrane (and possibly in the Trinity and Feather River terranes) in Early Devonian time (~400 Ma), suggesting continued arc magmatism. During Middle Devonian time (~380 Ma) an inverted metamorphic gradient developed in the Central Metamorphic Belt, coincident with serpentinization of the Trinity terrane, and portions of the Yreka terrane were metamorphosed. A critical constraint on the tectonism responsible for these events is that the rocks thrust over the Central Metamorphic Belt must have been at temperatures >650°C at a depth of 15 km (Peacock, 1987b). The Trinity terrane was probably cooler than this, however, because it was ~90 m.y. old at the time, and only oceanic lithosphere younger than 8 m.y. old is hotter than 650°C at 15 km (Parsons and Sclater, 1971). Three possible ways that the Central Metamorphic Belt could have been thrust beneath hot material associated with the Trinity terrane are: (1) the Central Metamorphic Belt was thrust beneath a portion of the Trinity terrane heated by arc magmatism (Fig. 4A); (2) the Central Metamorphic Belt was initially thrust beneath young, hot,

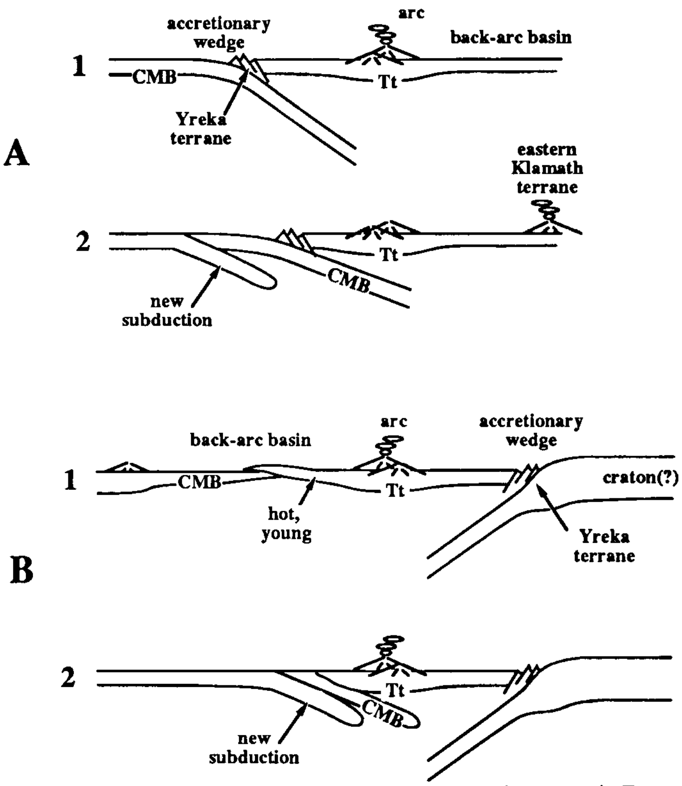

Figure 4. Possible tectonic settings for the Klamath-Sierran arc in Devonian time. This figure is labeled with rock units of the Klamath Mountains, but may apply to the Sierra Nevada as well. A, The Central Metamorphic Belt is thrust beneath a portion of the Trinity terrane that has been heated by arc magmatism. Perhaps the angle of subduction shallowed. B, Back-arc closure thrusts Central Metamorphic Belt rocks beneath hot, young back-arc lithosphere. This is similar to the situation envisioned by Boudier and others (1988) for the Oman ophiolite. This thrusting may have begun because continental material such as the Yreka terrane entered the old subduction zone. Metamorphism of the Central Metamorphic Belt occurred while the Central Metamorphic Belt was subducted beneath young back-arc lithosphere that has since been eroded. Further closure thrust the Trinity terrane over the Central Metamorphic Belt, causing serpentinization of the Trinity terrane. Isostatic uplift of the partially subducted craton may have allowed emplacement of the continentally derived Yreka terrane onto the Trinity terrane by low-angle normal faulting—analogous to the emplacement of the continentally derived Batinah allochthons onto the Oman ophiolite (Woodcock and Robertson, 1982). CMB = Central Metamorphic Belt; Tt = Trinity terrane.

back-arc lithosphere and only later beneath the Trinity terrane (Fig. 4B); or (3) the Central Metamorphic Belt was thrust beneath the Trinity terrane in Silurian time, and the Devonian metamorphic ages reflect later cooling. In case 2, thrusting may have begun along a spreading center between two young oceanic back-arc plates. Refrigeration of the Central Metamorphic Belt necessary for preservation of its inverted metamorphic gradient was accomplished by subduction of more material beneath the Central Metamorphic Belt. All three possibilities require that more than one subduction zone was active.

CONCLUSIONS

Detailed optical microscopy, back-scattered electron microscopy, and electron microprobe studies reveal that the Central Metamorphic Belt and Trinity terrane in the Klamath Mountains and the Feather River terrane of the Sierra Nevada contain similar protoliths and metamorphic parageneses. These data, combined with similar ages of metamorphism and relations with surrounding units, permit potential correlations between the Sierra Nevada and Klamath Mountains. The Trinity terrane is a multiply intruded intraoceanic arc composed of Ordovician to Devonian(?) ultramafic and mafic rocks. The Feather River terrane is also a polygenetic ophiolite with pre-Devonian to pre-Carboniferous ultramafic and pre-Devonian to Triassic mafic rocks. Both were metamorphosed during Devonian time at peak temperatures of 475° to 570°C. The Central Metamorphic Belt is a slice of oceanic crust accreted to the base of the Trinity terrane; the Feather River terrane also contains oceanic crust faulted against ultramafic rocks. Mafic and sedimentary rocks in both mountain belts were metamorphosed at temperatures of 500° to 650 ± 50°C and pressures of 500 ± 300 MPa. An inverted metamorphic gradient formed in the Central Metamorphic Belt during subduction beneath the Trinity terrane. Our correlation of the Central Metamorphic Belt and Trinity terrane of the Klamath Mountains and the Feather River terrane of the Sierra Nevada emphasizes large-scale similarities, and is intended to stimulte investigations of smaller scale differences that will ultimately provide a more detailed description of the early to middle Paleozoic evolution of the Klamath Mountains and Sierra Nevada.

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