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Structure and tectonics of the Bear Mountains fault zone and western Foothills terrane between Lake Don Pedro and Lake McSwain, central Sierra Nevada, California

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**Structure and tectonics of the Bear Mountains fault zone and
western Foothills terrane between Lake Don Pedro and Lake
McSwain, central Sierra Nevada, California**

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San Jose State University, 1993

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STRUCTURE AND TECTONICS OF THE BEAR MOUNTAINS FAULT ZONE AND
WESTERN FOOTHILLS TERRANE BETWEEN LAKE DON PEDRO AND
LAKE MCSWAIN, CENTRAL SIERRA NEVADA, CALIFORNIA

A Thesis

Presented To

The Faculty of the Department of Geology
San Jose State University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

By

Thomas Francis Barry

May 1993

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ABSTRACT

The western Foothills terrane and the Bear Mountains fault zone in the central Sierra Nevada are composed of fault-bounded blocks of Upper Jurassic island-arc volcanic rocks, syntectonic epiclastic rocks, tectonic melange containing exotic blocks, and Late Jurassic and Cretaceous intrusive bodies. These rocks (except the youngest intrusive rocks) strike northwest and generally dip steeply to the northeast. A regionally developed northwest-striking cleavage is subparallel to bedding and contains a lineation which rakes 85° - 120° from north. Metamorphism is commonly of greenschist-grade.

The 500-km-long, 2- to 5-km-wide, Bear Mountains fault zone was active from Middle Jurassic or earlier into the Early Cretaceous. In the study area this fault zone consists of three parallel, northwest-trending, high-strain domains, which are contained in Upper Jurassic volcanic and epiclastic rocks. Tectonic melange is exposed within the westernmost high-strain domain. It includes high-pressure garnet amphibolite blocks, ranging from < one to a few meters in width, that are surrounded by sheared serpentinite, which in turn is contained in an Upper Jurassic slate matrix. A pre-melange foliation is defined in the amphibolite blocks by alignment of sodic hornblende. These high-pressure rocks probably represent the ophiolitic

basement of the Foothills terrane and were mixed with syntectonic sediment as the terrane was rotated to steep dips at about 150 Ma.

Rocks east of the Bear Mountains fault zone are weakly metamorphosed, lack a thick Upper Jurassic volcanic sequence, and contain more coarse-grained metasedimentary rocks than the units west of the fault zone. These lithologic differences across the Foothills terrane, along with the contrasts in metamorphic grade and the steeply plunging stretching lineation within the Bear Mountains fault zone, suggest large-scale, east-over-west, displacement across the fault zone. Movement along the Bear Mountains fault zone, combined with intrusion of plutons, resulted in tectonic burial and greenschist-facies metamorphism of the western Foothills terrane.

INTRODUCTION

Geologic Setting

The western metamorphic belt of the central Sierra Nevada is located east of the Great Valley sequence and west of the Sierra Nevada batholith (Fig. 1). This belt consists of Paleozoic and Mesozoic rocks which, in a complex series of events, were buried, faulted, intruded, metamorphosed, uplifted, leveled, and uplifted again (Clark, 1964; Hill, 1975).

These rocks have been divided into four major tectonostratigraphic terranes, which are bounded by moderately to steeply northeast-dipping, northwest-vergent thrust faults (Fig. 2; Schweickert et al., 1988). The easternmost and structurally highest terrane is the Shoo Fly Complex, which consists of lower Paleozoic sedimentary and volcanic arc rocks that have undergone polyphase metamorphism.

The Calaveras-Shoo Fly thrust fault places the Shoo Fly Complex over the Calaveras Complex (e.g., Schweickert et al., 1988). The Calaveras Complex consists of deformed late Paleozoic to Lower Triassic chert, phyllite, and argillite with lesser amounts of limestone and basalt. This complex may represent oceanic sediment that was underplated during subduction (Paterson and Sample, 1988).

The Don Pedro terrane lies west of the Calaveras

Figure 1. Map of the western metamorphic belt and the Foothills fault system, adapted from Clark (1960). The study area is located between the Tuolumne River and the Merced River.

Figure 2. Terranes and major bounding faults in the western metamorphic belt, adapted from Paterson (1989). BMFZ = Bear Mountains fault zone, CSFT = Calaveras-Shoo Fly thrust, GIC = Guadalupe igneous complex, H = Hornitos pluton, MFZ = Melones fault zone, SF = Sonora fault, TUC = Tuolumne ultramafic complex.

Complex and is separated from it by the ductile Sonora fault (Schweickert et al., 1988). The Don Pedro terrane contains strongly deformed Lower to Middle Jurassic volcanic and sedimentary rocks which have been metamorphosed to the greenschist facies (Bateman et al., 1985). The most common metavolcanic rocks were originally pillow basalt and pillow breccia.

The Melones fault zone separates the Don Pedro terrane from the structurally underlying Foothills terrane, which consists of variably metamorphosed volcanic, sedimentary, and plutonic rocks (Clark, 1964). Within the Foothills terrane, three parallel, northwest-trending, fault-bounded belts of Upper Jurassic slate are separated by two distinct metavolcanic rock assemblages (Mannion, 1964; Fig. 3). The Bear Mountains fault zone, which is roughly coincident with the central slate belt, has been described as the central melange belt of the Foothills terrane (Miller and Paterson, 1991). East of the Bear Mountains fault zone, Upper Triassic-Lower Jurassic metavolcanic rocks and the eastern slate belt compose the eastern Foothills terrane. The western slate belt and Jurassic metavolcanic rocks west of the Bear Mountains fault zone comprise the western Foothills terrane.

Purpose

The Bear Mountains fault zone is the major structure of

Figure 3. Geology of a portion of the Foothills terrane, central Sierra Nevada, after Wahrhaftig and Clark (1962). The western slate belt consists of the Merced Falls Formation. The central slate belt consists of the Salt Springs Formation. The eastern slate belt consists of the Mariposa Formation.

the Foothills terrane. Its tectonic implications, however, are controversial. Some workers (Schweickert and Bogen, 1983) downplayed the significance of this 300-km-long fault zone, contending that the large-scale structure of the Foothills terrane is dominated by folds, with little displacement across the fault. Several recent studies, however, have cited evidence of major-scale tectonic mixing within the Bear Mountains fault zone and have argued for major displacement across this structure (Newton, 1983; Tobisch et al., 1989; Miller and Paterson, 1991).

Several plate tectonic models call for sinistral strike-slip displacement along the Sierran arc during the Late Jurassic (Engelbreton et al., 1985; Ave Lallemant and Oldow, 1988; McLaughlin et al., 1988; Wakabayashi, 1992). The Bear Mountains fault zone has been suggested as one of the structures recording this displacement (Ave Lallemant and Oldow, 1988; Wolf and Saleeby, 1992). However, detailed studies of the Bear Mountains fault zone, south of the study area of this paper, document Late Jurassic to Early Cretaceous dip-slip with an east-over-west sense of shear (Paterson et al., 1987; Tobisch et al., 1989).

The purpose of this study is to: map the units and the structures of the Bear Mountains fault zone and western Foothills terrane between Lake McSwain and the southern end of Lake Don Pedro (Fig. 3) at a 1:24,000 scale; determine the timing and style of deformation; and interpret the

significance of this deformation for the tectonic evolution of the Sierra Nevada.

Structural relations between units and small-scale structures were examined to define the limits of the Bear Mountains fault zone and the style of deformation in the Foothills terrane. Stretching lineations were measured to help determine whether displacement was predominantly strike-slip or dip-slip. Relationships within the study area were compared with those in areas along strike to the southeast and northwest within the Foothills terrane in order to present a synthesis of the metamorphic and deformational history of the Foothills terrane in the central Sierra Nevada.

Location of Study

The study area is located in the central Sierra Nevada foothills east of Modesto and northeast of Merced (Fig. 1). Lake McSwain on the Merced River is the southern boundary of the area. The northern border corresponds with the southern end of Lake Don Pedro. The area is bordered on the east by Lake McClure and on the west by the Don Pedro Golf Course and Merced Falls Road (Plates 1 and 2). Plates 1 and 2 correspond to the U.S. Geological Survey 7-1/2 minute Penon Blanco Peak Quadrangle and Merced Falls Quadrangle, respectively.

Previous Work

The western Sierra Nevada has been the subject of geologic interest since the Gold Rush of 1849-50. Rock units in the central Sierra Nevada were mapped first by Turner and Ransome (1897). The Melones and Bear Mountains fault zones were subsequently mapped as the Foothills fault system by Clark (1960; Fig. 1). Before this report, the most detailed work conducted in the study area was a transect along the Merced River, which was one of a series of transects along major streams in the western Sierra Nevada carried out by Clark (1964). Mannion (1964) mapped the La Grange 15-minute Quadrangle directly northwest of the present study area. The eastern Foothills terrane was mapped and studied by Bogen (1983, 1984, 1985). The study area also was examined in reconnaissance by Schweickert and colleagues, who have discussed it in their regional tectonic syntheses (e.g., Schweickert and Bogen, 1983; Schweickert et al., 1988). Deformation in the Foothills terrane immediately south of the study area has been studied by Tobisch et al. (1987, 1989), Paterson et al. (1987), Paterson (1989), and Miller and Paterson (1991).

THE FOOTHILLS TERRANE

The Foothills terrane is composed mostly of Mesozoic volcanic arc rocks and clastic rocks that are metamorphosed primarily to the greenschist facies (Clark, 1964). At the latitude of the study area the Foothills terrane can be divided into eastern, central, and western zones, as it has been to the south (Tobisch et al., 1989; Fig. 4). The Bear Mountains fault zone comprises the central Foothills terrane. This fault zone juxtaposes Upper Triassic-Lower Jurassic arc rocks of the eastern Foothills terrane against Upper Jurassic arc rocks of the western Foothills terrane.

The eastern and western Foothills terrane and the Bear Mountains fault zone each contain a steeply-dipping, northwest-striking, slate belt. These three slate belts are separated by two units of volcanic and volcanoclastic rocks, the Gopher Ridge Formation and the Penon Blanco Formation (Fig. 3). Earlier workers correlated the slate belts on the basis of lithologic similarities. However, the structure and stratigraphy are complex, biostratigraphic data are sparse, and such correlation may be unjustified (Clark, 1964).

The eastern Foothills terrane consists of the Upper Triassic-Lower Jurassic Penon Blanco Formation and the Upper Jurassic Mariposa Formation (Bogen, 1984). The western Foothills terrane consists of the metavolcanic Upper Jurassic Gopher Ridge Formation and the metasedimentary

WESTERN FOOTHILLS TERRANE	BEAR MOUNTAINS FAULT ZONE	EASTERN FOOTHILLS TERRANE	AGE Ma
	Copper Hill Formation		
Merced Falls Formation	Salt Springs Formation	Mariposa Formation	155
Gopher Ridge Formation		 30-40 Ma gap 	
		Penon Blanco Formation	
			Late Triassic- Early Jurassic

Figure 4. Stratigraphic relations in the Foothills Terrane. Based on Clark (1964) and Bogen (1983).

Upper Jurassic Merced Falls Formation (Clark, 1964). These two formations are structurally interleaved and may be in fault contact throughout the study area.

The Bear Mountains fault zone is defined by a northwest-trending, 2-to 5-km-wide shear zone, which contains three traceable high-strain domains (Plates 1 and 2). The fault zone consists of serpentinite-matrix melange, relatively coherent slices of the metasedimentary Upper Jurassic Salt Springs Formation and the metavolcanic Upper Jurassic Copper Hill Formation, and Late Jurassic-Cretaceous (?) intrusive rocks. Amphibolite blocks, which are contained in the serpentinite matrix, may represent slivers of the Foothills terrane basement (Miller and Paterson, 1991).

Contacts are generally poorly exposed within the study area. However, the topography of foothills and valleys clearly reflects lithologic changes. Volcanic rocks tend to form resistant ridges, whereas epiclastic units form valleys. Slate generally crops out as tombstone-like slabs which parallel the regional cleavage. However, it is almost impossible to trace any particular bed between "tombstones." Rocks within the Bear Mountains fault zone commonly are poorly exposed. However, road cuts, stream channels, and quarries provide good views of structure and access to fresh samples.

Eastern Foothills Terrane

The eastern Foothills terrane lies a short distance east of the study area, and Lake McClure covers much of its contact with the Bear Mountains fault zone (Plate 1), which is the western boundary. The eastern boundary is the Melones fault zone, which separates the Mariposa Formation from the Don Pedro terrane. Some reconnaissance work was done in the eastern Foothills terrane in order to confirm rock descriptions and mapping done by previous workers (Clark, 1964; Bogen, 1983).

Lithologic units

The eastern Foothills terrane is composed the Upper Triassic-Lower Jurassic Penon Blanco Formation and the Upper Jurassic Mariposa Formation (Fig. 4). The Penon Blanco Formation is exposed west of, and is paraconformably overlain by, the Mariposa Formation (Bogen, 1984; Tobisch et al., 1987).

Basement rocks. The basement of the eastern Foothills terrane and perhaps the entire Foothills terrane is thought to be composed of serpentinite-matrix melange with blocks and slabs of disrupted upper Paleozoic ophiolite (Sharp, 1988). These rocks are not exposed in the eastern Foothills terrane at the latitude of the study area, but crop out approximately 20 km north of the area. Basement rocks may be

represented in the study area by small blocks in the Bear Mountains fault zone described below.

Penon Blanco Formation. The Penon Blanco Formation, which presumably overlies the disrupted Paleozoic ophiolite, consists of pyroclastic rocks and mafic-to-intermediate volcanic flows that are mainly metamorphosed to the lower part of the greenschist facies (Morgan, 1976). Tuff, tuff breccia, augite-plagioclase porphyry, and tuffaceous graywacke are common (Bogen, 1985). Metavolcanic flows of intermediate composition are well exposed south of Highway 132, east of Piney Creek. Fresh samples are green, whereas weathered varieties are characteristically a dark-rusty-red color. Pillow structures were observed near Horseshoe Bend along the east-west arm of Lake McClure (Fig. 3).

Northwest-trending lenses of chert and metatuff within the Penon Blanco Formation crop out near Hunter Valley east of Lake McClure (Clark, 1964). The contact between the chert and metavolcanic rocks is mineralized, and was heavily mined in the past (Laizure, 1928); it probably is a fault.

Mariposa Formation. The Mariposa Formation rests paraconformably on the Penon Blanco Formation (Bogen, 1984). The Mariposa Formation consists mostly of slate, tuff, graywacke, and conglomerate. Fossils are relatively common in this unit. "*Beleminites*" *pacificus* and *Buchia concentrica*

(a marine bivalve) date the Mariposa Formation as late Oxfordian-early Kimmeridgian (Clark, 1964). An age of 155 Ma was given for portions of the formation by Bateman and Clark (1974). Metamorphic grade is lower-greenschist to prehnite-pumpellyite facies (Tobisch et al., 1989).

Structure

Penetrative northwest-striking foliation and associated lineation, which are prominent throughout the western Foothills terrane and Bear Mountains fault zone, are weakly developed in the eastern Foothills terrane. Cleavage is best developed in metasedimentary rocks. Bedding and cleavage are almost invariably parallel and steeply dipping, and lineation plunges steeply. The long axes of clasts in conglomerates and sandstones, and fragments in tuffaceous rocks and breccias, help define these fabrics (Evans and Bowen, 1977).

The lowest exposed portion of the Penon Blanco Formation occurs along the eastern shore of Lake McClure at Piney Creek (Plate 1; Clark, 1964). At this location, a high-strain domain, which represents the eastern limit of the Bear Mountains fault zone, cuts the Penon Blanco Formation. The top of the Penon Blanco Formation lies toward the east, where the unit is overlain by the Mariposa Formation. Bogen (1983) observed growth faults, which cut the Mariposa-Penon Blanco contact and affect thicknesses in

the Mariposa Formation. He concluded that the contact is depositional.

Comparison to other parts of the eastern Foothills terrane

Northeast of the study area the upper Paleozoic Tuolumne ultramafic complex (Fig. 2), which is unconformably overlain by the Penon Blanco Formation (Sharp, 1988), is inferred to represent the basement of the eastern Foothills terrane (Saleeby, 1982). Between the Stanislaus River and the Cosumnes River (Fig. 1), the Mariposa Formation interfingers with, and is overlain by, the Upper Jurassic Logtown Ridge Formation (Clark, 1964; Bogen, 1984). The latter formation consists of unfoliated, weakly deformed volcanic flows, breccias, and volcanoclastic sedimentary rocks, that are typically metamorphosed to sub-greenschist facies (Zhai and Day, 1992). Equivalents of the Logtown Ridge Formation are apparently absent at the latitude of the study area.

Bear Mountains Fault Zone

The 300-km-long, north-northwest-striking Bear Mountains fault zone is one of the major structures of the Foothills terrane (Clark, 1964). It is a structurally complex, 2- to 5-km-wide zone of tectonic mixing (Miller and Paterson, 1991). Geophysical data suggest that the Bear Mountains fault zone dips steeply to the east-northeast

(Carle et al., 1989). The fault zone was active from Middle Jurassic or earlier into the Early Cretaceous (Miller and Paterson, 1991).

The Bear Mountains fault zone contains both highly disrupted zones characterized by small (< a few meters wide) blocks, as well as relatively coherent sequences of greenschist-facies metasedimentary and metavolcanic rocks. These coherent domains range up to tens of kilometers in length. Blocks of exotic rocks of higher metamorphic grade occur locally within the disrupted zones (Miller and Paterson, 1991). Younger intrusive bodies are also present. Miller and Paterson (1991) inferred that early deformation formed a serpentinite-matrix melange prior to and during the Late Jurassic, and subsequent Late Jurassic to Early Cretaceous movement formed the intense and polyphase shear zones.

Some workers have suggested that sinistral strike-slip displacement occurred along this structure during the Late Jurassic (Wolf and Saleeby, 1992). However, others (Paterson et al., 1987; Tobisch et al., 1989; Miller and Paterson, 1991) contend that the nearly down-dip orientation of stretching lineation, combined with geochronological data, suggest that Late Jurassic to Early Cretaceous movement in the fault zone had an oblique, but mostly dip-slip, east-over-west sense of shear.

In the study area the Bear Mountains fault zone is a

2- to 3-km-wide zone of tectonic mixing and consists of three parallel and traceable high-strain domains. A well developed cleavage dips steeply to the northeast. Stretching lineations consistently plunge steeply. The fault zone contains and parallels the central slate belt of the Foothills terrane (Fig. 3). It is likely that stratigraphic units are repeated within the fault zone, but this is difficult to demonstrate because of the lack of marker beds.

Lithologic units

The Bear Mountains fault zone contains tectonic melange, metasedimentary rocks of the Upper Jurassic Salt Springs Formation, metavolcanic rocks of the Upper Jurassic Copper Hill Formation, and granitoid intrusions (Fig. 4). Blocks of local and exotic units, including sheared and massive serpentinite and medium-grade metamorphic rocks, are set in a slate-metagraywacke matrix within a 5-km-long melange belt. This belt is part of the westernmost high-strain domain (Plate 1). Metasedimentary rocks bound the melange and form the central slate belt, which is part of the Salt Springs Formation (Clark, 1964). Metavolcanic rocks within the Bear Mountains fault zone, exposed east of the Salt Springs Formation, are tentatively correlated with the Copper Hill Formation of Clark (1964), which overlies and intertongues with the Salt Springs Formation north of the study area. A pluton of possible Late Jurassic or Early

Cretaceous age referred to as "the Don Pedro Stock" by Mannion (1964) has intruded the Bear Mountains fault zone at the northern boundary of the study area.

Melange Rocks. In a 5-km-long belt within the fault zone, sedimentary breccia, metavolcanic rock, gabbro, and garnet amphibolite occur as blocks surrounded by serpentinite, which in turn is contained in a slate matrix (Plate 1). Six blocks of garnet amphibolite, ranging from 1-5 m in diameter (Fig. 5), were observed in this belt. The locations of these blocks are marked by the symbol "A" on Plate 1.

These amphibolites contain blue-green (Z) hornblende, albite, muscovite, epidote, and sphene. Mogk (in Miller and Paterson, 1991) determined that the hornblende is barroisitic (a sodic hornblende). The presence of barroisitic hornblende, white mica, and albite is indicative of relatively high pressure (typically 6 kbar or more) and higher P/T than other types of hornblende (e.g., Platt, 1975). The hornblende crystals define a strong foliation, although lineation is not apparent within the amphibolite blocks. Hornblende grains are commonly zoned; cores are blue-green and rims are green. Quartz and calcite veins are common in the blocks.

Matrix-supported sedimentary breccias occur as blocks that are typically a meter or less in diameter. A sample of

Figure 5. Photograph of an amphibolite block in serpentinite melange. Located west of Merced Falls Road near the southern end of the melange belt (Plate 1).

breccia from the melange belt (Plate 1; SW 1/4 NE 1/4 sec. 16, T. 3 S., R. 15 E.) contains rounded to angular clasts, 1-10 cm in diameter, that include metamorphosed radiolarian (?) chert, metagabbro, metadiabase, and chloritized intermediate metavolcanic rock. These clasts are set in a strongly foliated slate-metagraywacke matrix. The matrix has undergone greenschist-facies metamorphism, as indicated by the presence of chlorite and white mica in slate and small actinolite needles in metagraywacke. Foliation is defined by chlorite and white mica.

Miller and Paterson (1991) described small (< 10 m wide) clinopyroxene and hornblende gabbro blocks within serpentinite in the melange belt. They noted that the gabbro is cut by numerous cataclastic zones, 1-5 mm wide, that also show evidence of low temperature metamorphism. A 1-m-wide block of rodingite, which may represent a hydrothermally altered gabbro dike, is exposed near the southern end of the melange belt.

Serpentinite forms a highly sheared matrix to the melange throughout the 5-km-long belt. It also occurs as massive blocks, ranging up to 2 m in diameter, that are enclosed within more strongly foliated serpentinite. The foliation in the matrix is generally parallel to the regional northwest-striking cleavage.

Salt Springs Formation. A 1.5- to 3-km-thick

structural sequence of slate and graywacke, that also includes minor amounts of conglomerate, is exposed within the Bear Mountains fault zone. These rocks are correlated with the Salt Springs Formation (Clark, 1964). The type section of this formation lies along the Cosumnes River, approximately 80 km north of the study area (Clark, 1964). The dominant rock type there is black sericitic slate. Graywacke and tuff are common, and conglomerate is less common.

Fossils in the Salt Springs Formation are rare. Clark (1964) collected *Buchia concentrica*, "*Belemnites*" sp., and *Phylloceras* sp. near the Cosumnes River. Imlay (in Clark, 1964) considered these marine fossils to be diagnostic of the late Oxfordian to early Kimmeridgian (Late Jurassic, approximately 155 Ma).

In the study area, the Salt Springs Formation is composed of slate, graywacke, and conglomerate, that are interbedded with volcanic rocks and intruded by hypabyssal rocks. The igneous and epiclastic rocks became foliated during greenschist-facies metamorphism.

Slate makes up approximately 80 percent of the formation. These rocks are black to tan on both fresh and weathered surfaces and contain secondary pyrite. Thin (1-2 cm) beds of graywacke are well preserved, despite the strong slaty cleavage. Cleavage is approximately parallel to bedding, dipping steeply to the northeast, and is defined by

alignment of chlorite and white mica.

Below the high water line 0.5 km north of Exchequer Dam (Plate 2), beds of strongly foliated and lineated pebble conglomerate, one meter or less thick, crop out as slabs a few meters in length. These conglomerates are clast supported and contain pebbles of chert, intermediate volcanic rock, slate, and minor quartzite, and larger rip-up clasts of slate. Most of the pebbles range from 0.5-2.5 cm in length. The shape ratio commonly reaches 10:5:1. Contacts with enclosing slates are abrupt. These beds probably represent channel fill material.

A plesiosaur locality described by Clark (1964) is located south of the McClure spillway where dark gray limestone lenses less than a meter thick are interbedded with black quartzose slate. The limestone is medium-grained calcarenite that displays rounded to angular calcite grains with black carbonaceous inclusions (Clark, 1964).

Metagraywacke beds, typically a few centimeters thick, are common within the slates at the south end of Lake Don Pedro near Highway 132. These beds, which are commonly boudinaged, grade upwards to slate. Tops of beds are generally to the east.

Sills and volcanic rocks of intermediate composition, which make up less than 5 percent of the Salt Springs Formation, are relatively common within the slates in the Lake Don Pedro area. Clark (1964) suggested that these rocks

may be correlative with the Copper Hill Formation.

Copper Hill Formation. Fault-bounded blocks of metamorphosed lava and volcanic breccia are exposed in a 1-km-wide and 20-km-long belt, which extends from McClure Point northward along Piney Ridge to the Lake Don Pedro area. These rock are tentatively correlated with the Copper Hill Formation (Plate 1; Clark, 1964). However, because these rocks occur as fault slices, definitive correlation is not possible.

The Copper Hill Formation consists of intermediate to felsic volcanic rocks, which resemble the Gopher Ridge Formation of the western Foothills terrane (Clark, 1964). No fossils have been found in the Copper Hill Formation. On the Consumnes River, the lower part of the formation is thought to overlie and intertongue with the Salt Springs Formation and may therefore be as old as late Oxfordian (Late Jurassic; Clark, 1964).

The volcanic rocks along Piney Ridge are medium to dark green on fresh surfaces and dark red to brown on weathered surfaces. These rocks are glomeroporphyritic, containing phenocrysts that were probably hornblende and plagioclase, but now are chlorite, epidote, and calcite. These secondary minerals record greenschist-facies metamorphism, and define a moderate foliation. Foliation is less developed, however, than in the Gopher Ridge Formation.

Don Pedro Stock. The pluton exposed in the northwest corner of Plate 2 was examined by Mannion (1964), who referred to it as the "Don Pedro Stock." Only a portion of this tonalitic pluton lies within the map area, and most of it is covered by Lake Don Pedro. It is oval shaped and is 2.8 km long and 2.0 km wide. The tonalites display a hypidiomorphic granular, porphyritic, medium-grained texture. Phenocrysts consist of euhedral to subhedral plagioclase. Grain size increases somewhat towards the center of the stock. Most of the rock contains approximately 60 percent plagioclase, 20 to 25 percent quartz, and 15 to 20 percent biotite and green (z) hornblende (Mannion, 1964). The proportion of hornblende to biotite appears to increase inward (Mannion, 1964). These mafic minerals are commonly chloritized.

The contact of the stock with the slate and volcanic rocks is somewhat irregular in map pattern. Numerous small dikes and sills extend into the slates for distances of 1-2 km south of the stock. The pluton does not appear to be sheared by the Bear Mountains fault zone, suggesting that it may be Cretaceous in age. Mannion (1964) noted that the stock was little affected by regional metamorphism and similarly suggested that it was post-tectonic.

Structure

Three distinct domains of tectonic mixing and high

strain comprise the Bear Mountains fault zone in the study area (Plates 1 and 2). These domains are characterized by mylonites, serpentinite-matrix melange, tectonic breccias, and deformed quartz veins. Collectively, these domains and the sedimentary and volcanic rocks between them form the large-scale zone of mixing which is defined as the Bear Mountains fault zone. A well-developed regional cleavage strikes northwest and dips steeply to the northeast throughout the Bear Mountains fault zone (Fig. 6a). Stretching lineations commonly lie at a small angle to the dip of foliation (Fig 6b).

The eastern high-strain domain, which is the eastern limit of the Bear Mountains fault zone, extends approximately 100 km and is 20-40 m wide (Clark, 1960). Along Piney Creek, this high-strain domain separates the Penon Blanco Formation on the east from a narrow block of the Copper Hill Formation that is exposed on Piney Ridge (Plate 1). This relatively narrow zone contains strongly deformed epiclastic rocks. Some outcrops exhibit an anastomosing foliation. Quartz veins are abundant and openly to tightly folded. Axial planes are parallel to foliation and hinge lines are parallel to the down-dip stretching lineation, which is defined by elongate clasts.

The central high-strain domain lies on the west side of Piney Ridge and is well exposed within Barret Cove Recreation Area at the south boat ramp (Plate 1). This

Figure 6. Schmidt net lower hemisphere plots of structural elements in the Bear Mountains fault zone and the western Foothills terrane: a. Poles to foliation; 76 total points. b. Stretching lineations; 41 total points.

domain is approximately 100-200 m wide, and can be traced for approximately 15 km. Metavolcanic breccia is common in this domain. In one approximately 10-m-long outcrop there is a transition over a distance of less than 2 m from almost undeformed breccia to strongly foliated greenschist that displays a S-C mylonitic fabric. This fabric is defined by fine-grained mica stringers and reveals a reverse slip sense of shear. The breccia is heterolithologic and clasts typically are 1-5 cm in diameter. Plagioclase grains are commonly bent. Stretched clasts define a down-dip lineation. Metatuffs exposed west of the south boat ramp are also intensely foliated and contain relatively coarse white mica and chlorite.

Approximately 1 km south of the boat ramp a monolithologic breccia crops out, which consists of undeformed porphyritic clasts supported in a strongly foliated greenschist matrix. The matrix wraps around the clasts, which range up to 10 cm in diameter.

Approximately 10 km north of Barret Cove within the central high-strain domain is Solambo mine. An open shaft reveals a contact between sheared, strongly foliated epiclastic rocks to the east and a less deformed metavolcanic unit to the west. The epiclastic rocks structurally taper out less than 1 km north of the mine.

The westernmost high-strain domain of the Bear Mountains fault zone extends from Old Exchequer Dam

northward through Kassabaum Flats to Lake Don Pedro (Plates 1 and 2). This domain is generally contained within the Salt Springs Formation. The most prominent feature of this domain is the northwest-trending melange belt that is generally 10-40 m wide and extends for approximately 5 km (Plate 1). This belt contains slices of serpentinite that forms the melange-matrix. The serpentinite matrix is in turn contained within a slate matrix.

The anastomosing foliation in strongly sheared serpentinite wraps around blocks of massive serpentinite, garnet amphibolite, sedimentary breccia, metavolcanic rock and other rock types. Fractures in blocks are commonly filled with calcite and quartz. The outer surfaces of the serpentinite blocks, which range up to 2 m in diameter, are strongly slickensided.

At Jenkins Hills, north of the ultramafic belt, the Don Pedro tonalite stock has intruded the western high-strain domain. North of the stock, this domain was mapped as the Fortynine fault by Mannion (1964). He noted that this fault truncates a tuff unit near Lake Don Pedro, but slates only locally show evidence of strong shear.

This western high-strain domain appears to be the western edge of the Bear Mountains fault zone. However, there is also evidence for strong deformation in some discrete shear zones within the western Foothills terrane (Mannion, 1964).

Structural relations in and near the southern part of the Don Pedro stock, which was mapped in this study, place important constraints on the timing of deformation in the Bear Mountains fault zone. This stock has an isotropic structure, and there is no exposed evidence of deformation in the pluton. However, structural patterns may record syn- to post-emplacement deformation that was concentrated in the wall rocks. Bedding and cleavage in these rocks bend around the pluton (Mannion, 1964; Turner and Ramesome, 1897). Furthermore, numerous foliated dikes and sills, typically 1-3 m in thickness, occur in the country rock near the margins of the stock along the southern shore of Lake Don Pedro. These small intrusions are similar to the Don Pedro stock in composition. However, they display a solid-state foliation that is defined by elongate quartz and aligned biotite. The isotropic structure within the stock suggests that it probably was emplaced sometime after the main phase of deformation, but the possibility that it behaved as a rigid body during later deformation cannot be ruled out.

Comparison to other parts of the Bear Mountains fault zone

North of the study area, between the Cosumnes River and Tuolumne River, the Bear Mountains fault zone is characterized by a semi-continuous, northwest-trending belt of ophiolitic melange that is bounded by belts of lower-grade slate and greenstone (Saleeby, 1982). The 164-Ma Pine

Hill complex intrudes this ophiolitic melange near the Cosumnes River (Springer, 1980a, b), indicating that mixing at that latitude was Middle Jurassic or older. Behrman (1978) described isolated blocks of metavolcanic and metagabbroic rocks near the Cosumnes River, which have been metamorphosed to the amphibolite facies. K-Ar hornblende analyses have yielded ages of 190 ± 2 , 191 ± 2 , and 170 ± 12 Ma (Behrman, 1978). These ages are broadly similar to K-Ar hornblende ages of between 190 and 200 Ma that Morgan (1976) obtained from blocks of garnet amphibolite and crossite-bearing metachert in melange along the basal thrust of the Tuolumne ultramafic complex (Figure 2). This thrust fault may be continuous with the eastern high-strain domain of the Bear Mountains fault zone exposed along Piney Creek (Plate 1).

South of the study area, the 151-Ma Guadalupe igneous complex (Fig. 2) intrudes the Bear Mountains fault zone and its western margin was deformed by syn-emplacement shearing (Tobisch et al., 1989; Vernon et al., 1989). Cleavage in this pluton and its wall rocks is invariably steeply dipping (Haeussler and Paterson, 1991). The syntectonic 150 Ma Hornitos pluton (Fig. 2) also intrudes the Bear Mountains fault zone and is strongly deformed (Tobisch et al., 1989). Both the Guadalupe and Hornitos plutons were deformed at temperatures as high as those of the upper amphibolite facies (Tobisch et al., 1989; Vernon et al., 1989).

Western Foothills Terrane

The rocks of the western Foothills terrane are primarily intermediate to silicic volcanic rocks and slate, with minor amounts of graywacke and tuff. The volcanic rocks, referred to as the Gopher Ridge Formation by Clark (1964), are exposed east of rocks of the western slate belt, which were named the Merced Falls Formation (Clark, 1964; Fig. 4). North of La Grange, the western slate belt is covered by Cenozoic rocks. North of Lake McSwain, a pluton has intruded the Gopher Ridge Formation.

Lithologic units

Gopher Ridge Formation. The volcanic rocks within the map area immediately west of the Bear Mountains fault zone are part of the Gopher Ridge Formation. The type section of this formation consists of almost 4,600 m of strata near the Stanislaus River (Clark, 1964; Fig. 1). This section consists mostly of metamorphosed pyroclastic rocks that range from very fine-grained tuff to coarse breccia. Silicified massive volcanic rocks that may represent lava flows are exposed near the Tuolumne River (Clark, 1964).

No fossils have been found in the Gopher Ridge Formation, but it probably is Late Jurassic age. The upper part of the formation interfingers with the Salt Springs Formation near the Cosumnes River, where Clark (1964) noted fossils of late Oxfordian to early Kimmeridgian age.

Within the study area the Gopher Ridge Formation has a structural thickness of approximately 4,000 m. The formation is composed of volcanic breccia, porphyritic lava, and tuff which have been metamorphosed to the greenschist facies, as indicated by the presence of epidote + albite + chlorite + actinolite. Fine-grained muscovite also is present in some of these rocks. Greenschist-facies metamorphism has converted igneous hornblende to actinolite which, in turn, is replaced in some rocks by chlorite and calcite. Amygdules are filled by chlorite, epidote, and calcite.

Unweathered exposures of metamorphosed lava and flow breccia are present west of Fortynine Gap (Plate 1). Porphyritic and pyroclastic textures are well preserved despite moderate to strong foliation. Trachytic texture is defined by plagioclase laths that appear to have flowed around phenocrysts of subhedral plagioclase and hornblende. Hornblende commonly is replaced by chlorite and calcite. Foliation is defined by chlorite and muscovite.

McSwain Pluton. North of Lake McSwain, a Jurassic (?) pluton has intruded the Gopher Ridge Formation (Clark, 1964; Plate 2). Herein, this intrusion is referred to as the McSwain pluton. The pluton is approximately 3 km long and 1 km wide and is elongate parallel to the structural grain of the Foothills terrane. The dominant rock types are tonalite

and granodiorite. The ratio of plagioclase to quartz appears to increase towards the center of the body.

The eastern portion of the pluton is cut by a shear zone, which is approximately 100 m wide. The strongly deformed granitoid within the shear zone displays an S-C fabric in places. Mafic minerals are commonly altered to chlorite and epidote within the shear zone. Aligned chlorite and elongate quartz define a solid-state (S) foliation, which is parallel to the regional northwest-striking foliation (Fig. 6a). Biotite stringers mark the relatively widely spaced (approximately 5 mm between surfaces) C surfaces. These microstructures and mineral assemblages are typical of deformation of granitoids under greenschist-facies conditions (e.g., Paterson et al., 1989).

A weak magmatic foliation is defined by alignment of plagioclase. This foliation can best be observed in the center of the pluton where the rocks are relatively plagioclase-rich and not involved in the shear zone.

The pluton and country rock have both been cut by Cretaceous gold-bearing quartz veins. A 1-m-wide, northwest-trending vein extends for about 200 m in the pluton.

Merced Falls Formation. The type section of the Merced Falls Formation is exposed in the study area, along the Merced River, near the town of Merced Falls (Clark, 1964; Plate 1). These rocks consist of mostly black to gray

sericitic slate with minor interbedded felsic tuff and have a structural thickness of more than 1,500 m. Thin (1- to 2-cm-thick) beds of graywacke make up less than 5 percent of the formation. Coarse-grained sandstone and conglomerate present in the slate belts farther east are absent in this unit. Mannion (1964) found *Buchia* southeast of La Grange, 5 km west of the study area, that date the slates as no older than late Oxfordian (Late Jurassic).

Foliation in the slates is defined by chlorite and muscovite. Actinolite needles define a stretching lineation in metatuffs, which plunges steeply to the southeast. Mannion (1964) reported andalusite in slates along strike north of the study area. Pyrite cubes, 0.5 cm or less in dimension, are common.

Structure

The western Foothills terrane consists of steeply dipping metavolcanic and metasedimentary rocks. These rocks are complexly interbedded in some locations, but are in fault contact in others. The steep northwest-striking cleavage is parallel to bedding and well developed in all rock types, except part of the McSwain pluton. Stretching lineations are consistently steeply plunging. Folds are common along contacts, but are rare elsewhere in the western Foothills terrane. Shear zones are concentrated within 20-30 m of the contact between the Merced Falls Formation and the

Gopher Ridge Formation, but are also present at places > 1 km from the contact.

The contact between the Gopher Ridge Formation and the Merced Falls Formation is poorly exposed in most places. The presence of mylonite zones and folds at numerous localities along this contact suggests that some displacement has occurred between the two units. The regional cleavage is parallel to axial planes of these folds, and hinge lines are parallel to the down-dip stretching lineation.

A 2-m-wide mylonite zone crops out along Merced Falls Road in volcanic rocks approximately 30 m from the contact between the Gopher Ridge Formation and the Merced Falls Formation. The rocks are intensely foliated and lineated. The foliation wraps around albite grains which have been rotated and display asymmetric strain shadows of fibrous quartz. Kinematic indicators yield inconsistent sense of shear at this locality.

Metatuff and metavolcanic breccia in the Gopher Ridge Formation along Lake McSwain also show increased strain as the contact with the Merced Falls Formation is approached. Approximately 20 m from the contact, stretched clasts in the breccia mark cleavage and steeply plunging lineation. Slip along spaced extensional crenulation cleavage planes has deformed the dominant cleavage into a sigmoidal pattern. The sense of curvature of the cleavage suggests west-side up displacement, which is opposite to that suggested for the

Bear Mountains fault zone (Miller and Paterson, 1991) and for most of the western metamorphic belt at this latitude (Schweickert et al., 1988). Northwest of the study area, Mannion (1964) also found evidence for local west-side up displacement.

At the contact with the Gopher Ridge Formation, the Merced Falls Formation displays two generations of cleavage. The regional cleavage strikes approximately N 10° W, and a crenulation cleavage strikes approximately N 40° W. The intersection of these cleavages forms a pencil structure, which plunges steeply to the northeast. Pyrite cubes in the slate display asymmetric pressure shadows of fibrous quartz which are rotated 20° counterclockwise from the cleavage plane.

Three generations of folds are exposed in the slate along the Lake McSwain spillway (Plate 1). Bedding is tightly folded (F1). Hinge lines plunge moderately to the north (Fig. 7). The regional cleavage (S1) is axial-planar to these folds. A moderately strong crenulation (F2) cleavage (S2) strikes 30° counterclockwise from the regional cleavage and cuts the F1 folds. S1, S2, and quartz veins are also moderately-tightly folded (F3). These folds plunge steeply to the southeast (Fig. 8). A third cleavage is parallel to the axial planes of these folds.

Folds and zones of increased shear, concentrated near the contact between the Gopher Ridge Formation and the

Figure 7. Photograph of folded (F1) bedding with axial planar (S1) cleavage at the McSwain spillway (Plate 2).

Figure 8. Photograph of folded (F3) cleavages (S1 and S2) and quartz vein at the McSwain spillway (Plate 2).

Merced Falls Formation, may have resulted from either differential movement due to the contrasts in lithology across the contact or from relatively large-scale displacement. The combination of poor exposure and high strain makes it difficult to determine whether the contact is a tectonically modified depositional contact or is a major discontinuity.

The shear zone that cuts the McSwain pluton and the wall rocks of the Gopher Ridge Formation lies approximately 1.5-2 km from the contact with the Merced Falls Formation. Silicified bedded metavolcanic lavas, exposed 200 m south the pluton, contain folded epidote-chlorite segregations and dikelets. Regional cleavage is axial-planar to these folds, which range from 5 cm to 1 m in amplitude, and hinge lines are parallel to lineation.

Comparison to other parts of the western Foothills terrane

Evidence for displacement within the western Foothills terrane northwest of the study area was presented by Mannion (1964). He mapped the Twin Gulch fault, which trends parallel to and approaches the contact of the Merced Falls Formation with the Gopher Ridge Formation east of La Grange (Fig. 3). This fault may continue its trend southward along the contact. The deformation observed along the contact in the study area may be related to this fault.

The Riley Ridge fault was mapped 3 km east of the Twin

Gulch fault within the Gopher Ridge Formation (Mannion, 1964). This northwest-trending fault is marked by two, 2- to 3-m-wide, breccia zones, which bound an "intrusive rhyolite" slice between felsic flows on the west and pyroclastic and epiclastic rocks on the east (Mannion, 1964).

Approximately 12 km south of the study area, rocks of the Gopher Ridge Formation have been intruded by the La Paloma pluton and the Santa Cruz Mountain pluton and metamorphosed to upper greenschist or lower amphibolite facies (Tobisch et al., 1989; Fig. 3). These plutons were deformed at higher temperatures than the McSwain pluton. The 149 Ma La Paloma pluton is weakly domainally deformed (Saleeby et al., 1989). Deformation in the 147 Ma Santa Cruz Mountain pluton ranges from weak to strongly mylonitic (Saleeby et al., 1989).

DISCUSSION OF METAMORPHISM AND DEFORMATION

Significance of Tectonic Blocks

The melange belt of the western high-strain domain contains evidence of large-scale displacement in the Bear Mountains fault zone. A broadly ophiolitic assemblage, including moderate-to-high pressure garnet amphibolites, occurs in this belt as blocks within sheared serpentinite matrix that is in turn contained in a slate matrix. Thus, at least three stages of tectonic development are represented: (1) metamorphism of the garnet amphibolite; (2) disruption and mixing of the blocks with serpentinite; and (3) mixing of serpentinite and associated rocks with Upper Jurassic sediment. The metamorphic contrast between the amphibolite blocks and the metasedimentary matrix suggests large displacement within the Bear Mountains fault zone.

Metamorphism of the amphibolites

Moderate-to high pressure/temperature garnet amphibolite tectonites have been linked to tectonic emplacement of ophiolites (Platt, 1975; Carpenter and Walker, 1992). Such amphibolites commonly form during the initial stages of subduction where crustal rocks are thrust beneath an overriding plate (e.g., Hamilton, 1988). Miller and Paterson (1991) contended that the high-pressure

amphibolite blocks in the melange in the Bear Mountains fault zone probably formed during the thrusting of a sheet of hot oceanic mantle peridotite over the basaltic protoliths. In contrast, amphibolite blocks in ophiolitic melanges elsewhere in the Sierra Foothills terrane have been interpreted to have formed in an oceanic fracture zone (Saleeby, 1982).

Garnet amphibolites also occur 20 km north of the study area, on strike with the eastern high-strain domain. These amphibolites and impure crossite-bearing metachert blocks lie in a melange along the basal thrust of the Tuolumne ultramafic complex (Sharp, 1988). These rocks have been interpreted as slabs of Paleozoic oceanic basement and overlying supracrustal rocks (Morgan, 1976) that were metamorphosed at pressures of 6 kbar (approximately 20 km) and temperatures of 500°C (Sharp, 1988). The garnet amphibolites were elevated to the surface prior to 200 Ma according to Morgan (1976) and Miller and Harwood (1989), whereas Sharp (1988) contended that they were uplifted at both 200 Ma and 178 Ma. The relative proximity and apparently similar P/T conditions makes it likely that these rocks are correlative with the amphibolites exposed in the study area.

Formation of the serpentinite melange

Uplift of the amphibolites in the Bear Mountains fault

zone may have involved tectonic mixing with serpentinite of the ophiolitic basement. Behrman (1978) noted that early Mesozoic disruption of the Foothills terrane basement and development of serpentinite-matrix melange probably involved subduction and/or transform deformation.

The timing of serpentinitization is important for understanding the origin of the melange within the Bear Mountains fault zone. Serpentinitization may have occurred during ocean-floor hydrothermal alteration at temperatures $>250^{\circ}\text{C}$ in an oceanic fracture zone (Marshall and Marshall, 1982). An oceanic fracture zone setting could explain the metamorphic contrast within the Bear Mountains fault zone, but it is not readily compatible with the relatively high P/T metamorphism of the amphibolites (Miller and Paterson, 1991). Thus, Miller and Paterson (1991) favored the hypothesis that the amphibolites formed during thrusting, were uplifted, eroded, and then the entire assemblage was incorporated into serpentinite melange prior to mixing with the Upper Jurassic sedimentary matrix. Mixing with serpentinite must have occurred sometime after the high-pressure metamorphism, because low-grade blocks also are contained in the serpentinite matrix.

Late Jurassic tectonic mixing

Serpentinite-matrix melange with its included blocks of amphibolite and other rock types is mixed with the Upper

Jurassic Salt Springs Formation in the Bear Mountains fault zone. This relationship indicates that the fault zone was active during or after deposition of these Upper Jurassic epiclastic rocks.

Nevadan Deformation

Some workers have attributed metamorphism and deformation in all four terranes of the central part of the western metamorphic belt to the Late Jurassic Nevadan orogeny (e.g., Schweickert et al., 1988). Recently, it has been shown that the effects of Nevadan orogenesis decreased eastward across the central Sierra Nevada, and east of the Melones fault zone Nevadan deformation was only domainal in development (Tobisch et al., 1987).

Tobisch et al. (1989) used U-Pb and Ar/Ar dating methods to constrain the timing of pre-metamorphic folding and faulting in the Foothills terrane to between 160 and 151 Ma, and showed that the development of cleavage by ductile deformation was clearly post-Nevadan (151-123 Ma). Bogen (1985) suggested that rocks in the Foothills terrane were rotated approximately 90° to steep dips by large-scale folding in a "trench-like setting" during the Nevadan orogeny. This interpretation is based on the assumption that the Mariposa Formation, Salt Springs Formation, and Merced Falls Formation are correlative and define large-scale anticlines (Bogen, 1983; Schweickert and Bogen, 1983). Other

workers do not see evidence for such large-scale folds (Miller and Paterson, 1991). The presence of the Bear Mountains fault zone is the strongest argument against the fold interpretation.

Rigid body rotation of arc rocks and syntectonic sediment was accommodated by the Foothills fault system prior to the main phase of metamorphism and formation of the regional cleavage (Tobisch et al., 1989). The Foothills terrane was rotated nearly 90° about a horizontal axis, in a clockwise sense. This interpretation is consistent with the presence of the Bear Mountains fault zone and the parallelism of the later-formed regional cleavage with the regional attitude of bedding (Tobisch et al., 1989). Rotation may have been accompanied by large-scale mixing along the Bear Mountains fault zone, such as that of the high-pressure garnet amphibolites in serpentinite and of the serpentinite in syntectonic epiclastic rocks. Melange formation has been constrained to prior to and during the Late Jurassic (Miller and Paterson, 1991).

Post-Nevadan Deformation

After tilting of the beds to steep dips, rocks of the Bear Mountains fault zone and western Foothills terrane underwent ductile deformation and greenschist-facies metamorphism from about 151-123 Ma (Tobisch et al., 1989). This ductile deformation is manifested by the steeply

dipping, northwest-striking cleavage that is prominent in the slates and also well developed in volcanic rocks.

Paterson et al. (1987) measured greater than 50% shortening in the western Foothills terrane, but less than 30% shortening in the eastern Foothills terrane. Cleavage and associated lineation began forming in the Bear Mountains fault zone at about 151 Ma, and then moved diachronously across the Foothills terrane from about 145 Ma until 123 Ma (Tobisch et al., 1989). Movement, which had a dominant east-over-west sense of shear with a small component of sinistral strike-slip, deformed the western margin of the 151 Ma Guadalupe igneous complex (Paterson et al., 1987; Tobisch et al., 1989). The rocks now exposed in the Foothills terrane were buried to a depth of 12 km during this deformation (Haeussler and Paterson, 1991).

This main phase of deformation in the Foothills terrane was probably driven by subduction to the west (e.g., Engebretson et al., 1985), arc-magmatism in the study area, and syn-magmatic, reverse movement along the Bear Mountains fault zone (e.g., Wakabayashi, 1992).

Late Cretaceous Mineralization

Copper-lead-zinc and gold-bearing quartz veins cut rocks and structures in all three zones of the Foothills terrane. These veins are concentrated along the Foothills fault system. More specifically, the Foothills copper belt

is more or less coincident with the Bear Mountains fault zone (Laizure, 1928). Mineralization of Mother Lode quartz veins has been dated as 120-115 Ma (Bohlke and Kistler, 1986) or 115-110 Ma (Tobisch et al., 1989). Temperatures of mineralization were between 250⁰-350⁰ C (Weir and Kerrick, 1987).

SUMMARY

The Foothills terrane consists of an eastern portion and a western portion, separated by the Bear Mountains fault zone. Deformation in the eastern Foothills terrane, which is composed of the Upper Triassic-Lower Jurassic Penon Blanco Formation and the Upper Jurassic Mariposa Formation, is weak and in places non-penetrative. The western Foothills terrane, which is composed of the Upper Jurassic Gopher Ridge Formation and Merced Falls Formation, has undergone strong penetrative deformation and greenschist-facies metamorphism. A thick sequence of Upper Jurassic metavolcanic rocks, corresponding to the Gopher Ridge Formation, is absent in the eastern Foothills terrane. Considerable amounts of coarse-grained volcanic graywacke and conglomerate are present in the Mariposa Formation, but are almost entirely lacking in the Merced Falls Formation. Thus, the epiclastic rocks of the western Foothills terrane are more distal than rocks in the eastern Foothills terrane, and they may be derived from different sources.

The Bear Mountains fault zone is a 300-km-long and 2- to 5-km-wide shear zone consisting of slate-metagraywacke-matrix melange that experienced intense polyphase deformation and metamorphism (Miller and Paterson, 1991). This study has shown that the fault zone consists of blocks

of local and exotic units, including high-pressure garnet amphibolite, that range from a few meters to several kilometers in length. These blocks are bounded by high-strain domains that consist of strongly foliated and lineated greenschist-facies rocks. The presence of high-pressure blocks suggests that large displacements juxtaposed amphibolites, which probably formed during the initial stages of subduction, with supracrustal rocks.

A northwest-striking cleavage is present throughout the western Foothills terrane and the Bear Mountains fault zone. This foliation parallels bedding which everywhere is steeply dipping. Lineations uniformly plunge steeply, and are close to down-the-dip of the cleavage. Sense-of-shear indicators generally suggest east-over-west movement. The main exception is along the Merced Falls-Gopher Ridge contact in the western Foothills terrane. Adjacent to this contact, heterogeneous shear zones display a second generation of cleavage, which strikes approximately 30° counterclockwise of the regional cleavage.

The presence of exotic high-pressure blocks, high-strain domains, and narrow discrete mylonite zones suggests large displacement across the western Foothills terrane and the Bear Mountains fault zone. The lack of a thick Upper Jurassic volcanic sequence in the eastern Foothills terrane, along with the lithologic differences in the metasedimentary rocks, also suggest large displacement across the Bear

Mountains fault zone. However, because units are not directly correlative across the fault zone, it is difficult to estimate the amount of displacement. The 300-plus-km length of the Bear Mountains fault zone suggests that several tens of kilometers of displacement would be reasonable. There is no direct evidence for sinistral strike-slip movement as has been proposed by some other workers. The steeply plunging stretching lineation provides strong evidence that the documented ductile strain results from dip-slip movement.

Tectonic History

The synthesis of the forementioned structural, stratigraphic, metamorphic, and age data allows the compilation of the following tectonic history for the Foothills terrane.

1. Initiation of subduction leading to garnet-amphibolite metamorphism in the Foothills terrane at about 200 Ma.
2. Upper Triassic-Lower Jurassic arc magmatism in the eastern Foothills terrane (Penon Blanco Formation).
3. Early movement along the Bear Mountains fault zone leading to incorporation of high-pressure rocks in the serpentinite-melange.
4. Epiclastic sediment deposited across the entire Foothills terrane contemporaneous with volcanism in the

central and western Foothills terrane at about 155 Ma.

6. Rigid rotation of the Foothills terrane after deposition of the epiclastic rocks, but before cleavage formation. Mixing of high-pressure rocks and serpentinite melange with sedimentary rocks.

7. Emplacement of the Late Jurassic plutonic suite at 151-147 Ma (151 Ma Guadalupe igneous complex, 150 Ma Hornitos pluton, 149 Ma La Paloma pluton, and 147 Ma Santa Cruz Mountain pluton).

8. Formation of the regional cleavages, metamorphism, and east-over-west movement on Bear Mountains fault zone at 151-123 Ma. Burial of rocks from 4 to 12 km.

9. Mineralization of the Mother Lode quartz veins at 120-115 or 115-110 Ma.

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37°45'

37°42'30"

GEOLOGY OF THE BEAR MOUNTAIN AND THE WESTERN FOOTHILLS

PENON BLANCO PEAK QUADRANGLE

MAPPED BY:
THOMAS F. BARRY

DATE: MARCH 1992

NOMENCLATURE

WESTERN FOOTHILLS TERRANE

BEAR MOUNTAIN

GRANITOID ROCKS
(DON PEDRO STOCK)

COPPER HILL FORMATION
METAVOLCANIC ROCKS
GREENSCHIST-GRADE,
MOSTLY INTERMEDIATE
AND PYROCLASTIC ROCKS

MERCED FALLS FORMATION -
BLACK TO GRAY SERICITE
SLATE W/ MINOR TUFF

SALT SPRINGS FORMATION
SLATE AND METAGRAY
MINOR CONGLOMERATE

GOPHER RIDGE FORMATION -
GREENSCHIST-GRADE
PYROCLASTIC ROCKS OF
INTERMEDIATE COMPOSITION
SOME PILLOW LAVA

OF THE BEAR MOUNTAINS FAULT ZONE		
THE WESTERN FOOTHILLS TERRANE		
N BLANCO PEAK QUADRANGLE, CALIFORNIA		
DATE: MARCH 1992	SCALE: 1:24000	PLATE NO:
	1 KILOMETER	1

NOMENCLATURE

LEGEND

This geological map depicts the Lake Don Pedro area, showing various geological units and topographic features. The map includes the following elements:

- Geological Units:**
 - Jss:** Jointed sandstone, shown in the upper left and upper right portions of the map.
 - Jum:** Jointed mudstone, located in the upper right portion of the map.
 - Jgrv:** Jointed gravel, shown in the lower portion of the map.
- Topographic Features:**
 - BEAR MOUNTAIN:** A prominent topographic feature on the right side of the map.
 - FLEETING CREEK:** A creek flowing from the top center towards the upper right.
 - BONDS FLAT:** A flat area located in the middle left portion of the map.
- Elevation Data:** Numerous spot elevations and contour lines are marked throughout the map, including values such as 60, 64, 65, 69, 70, 72, 75, 79, 80, 82, 85, and 88.
- Infrastructure:** A road labeled **132** is shown in the lower left corner.
- Other Markings:** The letters **A** and **B** are used to mark specific locations or points of interest on the map.

37°40'

GREENSCHIST-GRADE
PYROCLASTIC ROCKS OF
INTERMEDIATE COMPOSITION
SOME PILLOW LAVA

ION -

F
ITION

LEGEND

CONTACT	FAULT: HIGH-STRAIN DOMAIN	STRIKE & DIP OF BEDDING	STRIKE & DIP OF SCHISTOSITY OR CLEAVAGE

TREND & PLUNGE OF STRETCHING OR MINERAL LINEATION	TREND & PLUNGE OF FOLD AXIS OR PENCIL STRUCTURE	STRIKE & DIP OF WAVY FOLIATION	STRIKE & DIP OF JOINT
			SHEAR ZONE

NO VERTICAL EXAGGERATION

**DENOTES DIP
OF CLEAVAGE**

120°15'

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120°22'30"

120°20'

Jmf

Jg

120°17'30"

120°17'30"

120°15'

37°37'30"

37°35'

TREND & PLUNGE
OF STRETCHING
OR MINERAL
LINEATION

STRIKE & DIP
OF
SCHISTOSITY
OR CLEAVAGE

SHEAR
ZONE

NOMENCLATURE

WESTERN FOOTHILLS TERRANE

BEAR MOUNTAINS FAULT ZONE

GRANITOID ROCKS
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SLATE AND METAGRAYWACKE,
MINOR CONGLOMERATE & TUFF

GOPHER RIDGE FORMATION -
GREENSCHIST-GRADE
PYROCLASTIC ROCKS OF
INTERMEDIATE COMPOSITION
SOME PILLOW LAVA

UPPER JURASSIC

MERCED FALLS ROAD

SECTION B - B'

NO VERTICAL EXAGGERATION

DENOTES DIP
OF CLEAVAGE

37°32'30"

GEOLOGY OF THE BEAR MOUNTAINS FAULT ZONE AND THE WESTERN FOOTHILLS TERRANE

MERCED FALLS QUADRANGLE, CALIFORNIA

PREPARED BY: THOMAS F. BARRY

DATE: MARCH 1992

SCALE: 1:24000

1 KILOMETER

PLATE NO:

2

37°30'