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The structural and metamorphic history of the Oakhurst roof pendant, Mariposa and Madera counties, California

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THE STRUCTURAL AND METAMORPHIC HISTORY OF THE OAKHURST ROOF PENDANT, MARIPOSA AND MADERA COUNTIES, CALIFORNIA

by

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ABSTRACT

The Oakhurst roof pendant, near Oakhurst, California, consists of three pre-Cretaceous clastic metasedimentary rock units, surrounded and intruded by rocks of the Sierra Nevada batholith. Two zones of probable "sheared granitic" and "ultramafic" rocks trend northwesterly and are approximately aligned with the Foothills fault system farther north.

The dominant mesoscopic feature of the pendant is a northwesterly striking foliation which forms a downward converging fan. Earlier-formed hornblende lineations have been transposed into this foliation plane, as shown by Schmidt-net projections.

Rocks comprising the three units show three textural stages:

(1) Early amphiboles and diopside overgrown by later static amphibole pophyroblasts. Hornblende lineations in one of these units show a great-circle Schmidt-net distribution.

(2) A superimposed, well-developed, cataclastic s-plane (the mesoscopic foliation).

(3) Late, static growth of poikiloblastic micas and diopside, straight well-crystallized micas, near polygonal quartz and feldspar, epidote and biotite after amphibole

and diopside, and chlorite after biotite.

The "sheared granitic" and "ultramafic" rock bodies display the same prominant foliation and static and retrograde metamorphic textures as do rocks of the three major units.

These data are interpreted as reflecting three dominant post-sedimentary structural (D) and thermal (M) events:

(1) M_1/D_1 consists of episodes of synkinematic metamorphism, which resulted in an early foliation, $\underline{S}_1$, and of static metamorphism, M_1. M_1 is of the epidote-amphibolite facies.

(2) D_2 resulted in the cataclastic development of the prominent fanning foliation, $\underline{S}_2$; the fan is indicative of an antiformal structure. This antiform and foliation developed as a consequence of subvertical movement, as indicated by the geometry of transposition of hornblende lineations into $\underline{S}_2$. The "sheared granitic" and "ultramafic" rock bodies were emplaced along two shear zones during D_2. These zones could be the roots of thrust sheets and possibly an extension of the Foothills fault system, which has been mapped as terminating 20 miles to the northwest.

(3) M_2 was a static metamorphic event associated with batholithic intrusion. Locally, this event was characterized

initially by high temperatures, but retrograde conditions generally prevailed. M_2 was dominantly of the albite-epidote-hornfels facies, but locally of the hornblende-hornfels facies. Radiogenic dates of batholithic rocks near the pendant date M_2 as Late Jurassic-Middle Cretaceous. Therefore, M_1/D_1 and D_2 are pre-Late Jurassic.

M_1/D_1 may be a southerly expression of the Late Permian-Early Triassic Sonoma Orogeny. D_2 apparently reflects the deformation associated with the classical Nevadan Orogeny, and M_2 corresponds to late or post-orogenic granitic intrusion of the Sierra Nevada batholith.

CHAPTER I

INTRODUCTION

Purpose and Scope of Investigation

The purpose of this investigation was to study the structural and metamorphic history of a roof pendant in the Sierra Nevada batholith. Hereafter this pendant will be referred to as the Oakhurst roof pendant. It is located 20 miles southeast of the mapped termination of the Melones fault zone, a major component of the Foothills fault system (Clark, 1960; Fig. 1), and is made up of undifferentiated pre-Cretaceous metasedimentary rocks (Strand, 1967) that are surrounded and partly intruded by granitic rocks of the batholithic complex. Because of the location of the pendant, the possibility that the fault zone may extend south an unknown distance (Cloos, 1932) was pursued as a secondary objective of the thesis.

Location and Geography

The area of study is in east-central California, between the towns of Oakhurst, Coarsegold, and Ahwahnee, 40 miles northeast of Fresno and 20 miles southeast of Mariposa (Fig. 1). California Routes 41 and 49 are the major paved highways into the area. A number of well kept dirt roads traverse the pendant, making it easily accessible.

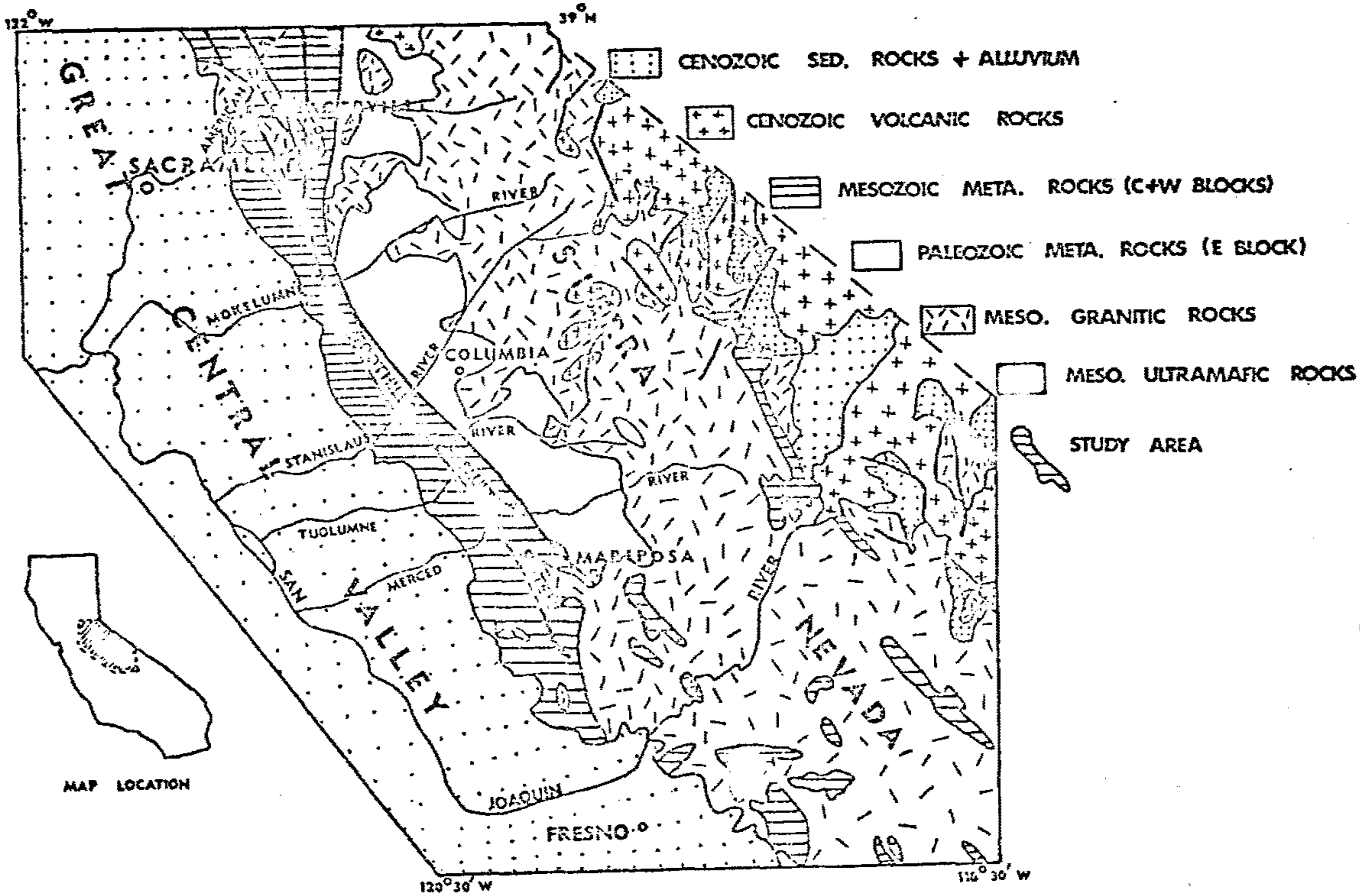


Figure 1. General geologic index map of the central Sierra Nevada region. E, C and W blocks in the explanation refer to the eastern, central, and western structural blocks discussed by Clark (1964).

The study area is moderately rugged, with a mature topography marked by narrow ridges and deep valleys. Deadwood Peak, at 4540 feet, is the highest point; the lowest point, approximately 1500 feet, is along the Fresno River. The only two permanent streams are the Fresno and Chowchilla Rivers. Annual rainfall reaches approximately 20-30 inches. Most precipitation occurs during the fall, winter, and spring, leaving the summer months extremely dry.

Local topography is lithologically controlled. The granitic rocks form lowlands, whereas the metamorphic rocks underlie ridges and topographic highs. The granitic lowlands are covered by grass and small shrubs, the metamorphic uplands by ponderosa pine, several species of oak, dense thickets of manzanita, chamise, and poison oak, as well as a variety of grasses. Because of this thick vegetative cover, rock exposures are patchy, and cross-country travel is difficult in places.

Techniques of Study

The metamorphic rocks of the pendant were divided into three units. Contacts within the mass were mapped as were the contacts with plutonic igneous bodies. Attitudes of foliation planes, lineations, and minor-fold axial planes and axes were measured. Field-oriented samples were collected and thin sectioned for use in petrographic and textural analyses. All mineral percentages listed in this thesis were determined by visual estimations. Finally, both Wulff and Schmidt nets were used to study and illustrate the structural trends and geometry of the region. Field work was accomplished during May, June, and July of 1971. Field mapping was done on USGS aerial photographs having a scale of 1/39,200.

Geologic Setting

The Sierra Nevada is a great block composed primarily of plutonic igneous and metamorphic rocks of Paleozoic and Mesozoic age. It has been faulted on the east, along the Sierra Nevada fault system, and tilted westward. On the west it is buried by Upper Cretaceous and Cenozoic sedimentary rocks of the Great Valley and on the north by Cenozoic volcanic rocks which extend southward from the Cascade Range. Most of the southern and northeastern sectors of the Sierra is composed of Mesozoic granitic plutonic rocks which comprise the Sierra Nevada batholith. The numerous plutons which make up the batholith were intruded into strongly deformed Paleozoic and Mesozoic metasedimentary and metavolcanic rocks, which, in the northern and central Sierra, make up the western Sierra Nevada metamorphic belt ("Mother Lode" region of earlier workers); in the southern Sierra, metamorphic rocks have been largely eroded, leaving only scattered roof pendants

(Bateman, 1968; Fig. 1).

Geology of the Western Sierra Nevada Metamorphic Belt

Stratigraphy

Rocks of the western Sierra Nevada metamorphic belt were deposited in part of the Cordilleran geosyncline and subsequently metamorphosed. They are broadly divisible into a bedrock complex of metamorphic and granitic rocks and a superjacent series of nearly flat-lying alluvial and volcanic deposits (Clark, 1964). The superjacent series is not considered in this report. The bedrock complex is made up of metasedimentary and metavolcanic rocks of Paleozoic and Mesozoic age as well as Mesozoic plutonic rocks. The metamorphic rocks are representative of a eugeosynclinal assemblage; their stratigraphic characteristics are summarized in Figure 2. Two northwesterly trending fault zones divide the metamorphic terrain into three structural blocks. Paleozoic metamorphic rocks are found chiefly in the eastern block; Mesozoic metamorphic rocks are found primarily in the central and western blocks (Clark, 1964; Figs. 1 and 3).

In addition to the major lithologic units in the region, plutonic rocks, serpentinites, and some greenschist also occur. These are briefly described below.

Structural Situation	Age	Formation or Group		Description
Western Block	Late Jurassic	Copper Hill Volcanics		Within and west of the Bear Mountains fault zone. Mainly pyroclastic in character and andesitic in composition. Primary structures and textures destroyed by strong shearing. 7,000 feet thick.
		Salt Springs Slate		Black sericite slate with some graywacke tuff, and conglomerate. Difficult to distinguish from Mariposa and Cosumnes formations.
		Gopher Ridge Volcanics		Largely pyroclastic with some massive and pillow lavas. Tuffs and volcanic breccia dominant. Composition varies from basaltic, to andesitic to rhyolitic to dacitic. 15,000 feet thick.
Central Block	Late Jurassic	Amador Group	Mariposa Formation	Black silty slates interbedded with tuff and graywacke. Brower Creek volcanic member is made up of green volcanic breccia interbedded with slate+conglomerate. 4,000 feet thick.
			Peñon Blanco Volcanics	Green tuffs, and volcanic breccias, interbedded with silicified ash. Some massive and pillow lavas. 15,000 feet thick.
			Logtown Ridge Formation	Volcanic breccia of mudflow origin and tuffs. 4,300 feet thick.
	Middle Jurassic		Cosumnes Formation	Interbedded graywacke and slate, tuff and black slate. Some conglomerate. 3,600 feet thick.
Eastern Block	Paleozoic	Calaveras Formation*	Chert Member	Chert interbedded with black carbonaceous quartzose slate, phyllite, garnet schist, limestone, and some volcanics and metavolcanics.
			Argillaceous Member	Black slate and massive siltstone interbedded with chert, tuff, phyllite, limestone, conglomerate, and graywacke.
			Volcanic Member	Volcanic breccia and conglomerate, tuff, and green phyllite, interbedded with black carbonaceous schists, cherts, and slates. Some pillow lava. 5,000 feet thick.
			Clastic Member	Fine grained interbedded slate, siltstone, graywacke, pyroclastics, and chert. Also a conglomerate-breccia of mudflow origin. 10,000 feet thick.

Figure 2. Generalized stratigraphic scheme for the rocks of the western metamorphic belt. Descriptions and terminology are after Clark (1964) who refers to metamorphic rocks retaining signs of original sedimentary structures by the names of their sedimentary parent rock types. *Calaveras Formation occasionally seen in the central block.

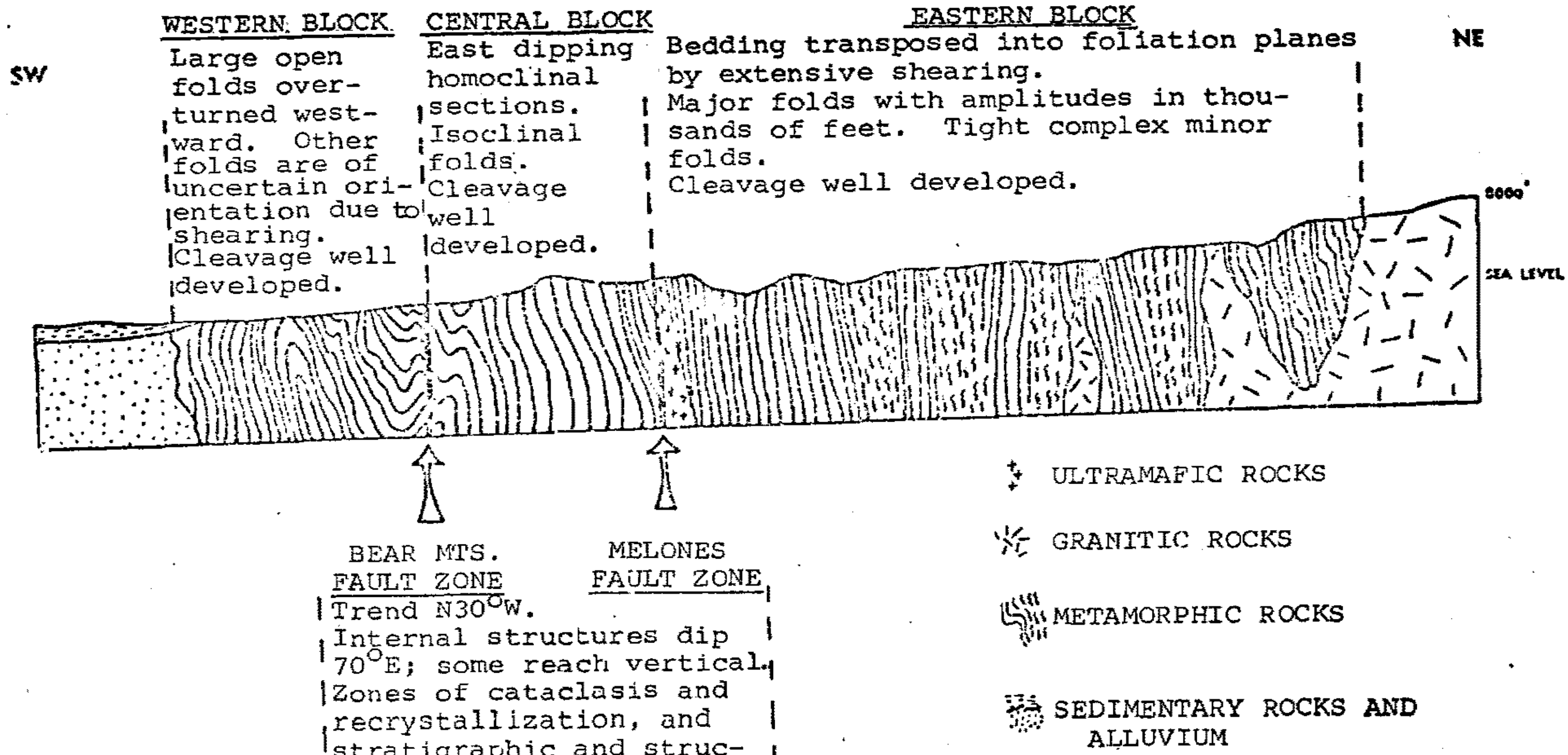


Figure 3. Generalized cross-section of the western metamorphic belt along the Merced River. Included are descriptions of the three structural blocks and the two major fault zones (after Clark, 1964).

Greenschist

This volcanic derivative crops out mainly within the major fault zones of the Foothills fault system. The rock is generally schistose, but may be associated with massive amphibolites. Most primary structures have been destroyed by alteration and penetrative deformation. Because these rocks occur in the fault zones, their age is uncertain. However, the presence of Paleozoic and Jurassic volcanics in these zones suggests that the green schist may be of both ages (Clark, 1964).

Serpentinites

Serpentinite is the most common ultramafic rock in the Sierra region. It occurs in bodies of varying dimensions, but commonly on a scale ranging from feet to miles. The serpentinite is blocky to foliated, and its surfaces may be strongly slickensided. Most is probably Late Jurassic in age, inasmuch as the faults which apparently control emplacement cut both Paleozoic and Jurassic rocks (Clark, 1964).

Plutonic Rocks

Plutonic rocks of the Sierra region are comprised of ultramafic rocks and rocks ranging from gabbro to granite in composition. Ultramafics, some serpentinized, occur in linear belts within the central and western structural blocks; the less mafic rocks constitute the Sierra Nevada batholith. East of the Melones fault zone the plutonic rocks are of granitic to granodioritic composition, while to the west the nonultramafic plutons are quartz diorites and gabbros. The granitic bodies are generally homogeneous and display sharp contacts with adjacent metasedimentary rocks (Clark, 1964).

Detailed radiogenic age studies in the Sierra region by Evernden and Kistler (1970) have revealed five separate epochs of intrusion. These are named for specific localities and are as follows:

Epoch	Age
Cathedral Range -	Upper Cretaceous (90 - 79 m.y.)
Huntington Lake -	Lower Cretaceous (121 - 104 m.y.)
Yosemite -	Upper Jurassic (148 - 132 m.y.)
Inyo Mountains -	Lower-Middle Jurassic (180 - 160 m.y.)
Lee Vining -	Middle-Upper Triassic (210 - 195 m.y.)

It is evident that the Sierra batholith is not a single homogeneous plutonic body, but a composite of numerous plutons which were intruded throughout much of the Mesozoic.

Synkinematic Regional Metamorphism

To date, no comprehensive studies of the regional metamorphism in the western metamorphic belt has been undertaken. However, it is clear that metamorphism of low grade predominates. Metamorphic grade apparently increases southward, perhaps due to the exposure of deeper structural levels. Even so, staurolite grade has been reported near Columbia (Baird, 1962).

Structural Geology

According to Clark (1964), the metamorphic belt of the western Sierra Nevada is situated on the western limb of a faulted synclinorium whose axial region is occupied by the Sierra Nevada batholith. However, Kistler and others (1971) believe that the Sierra region was a sediment source, rather than a geosynclinal downwarp receiving sediments, during batholith emplacement.

Bedding dips steeply eastward and strikes northwesterly, parallel to the axis of the Sierra. Major folds and apparently homoclinal sections (Clark, 1964) are truncated by the northwesterly trending Bear Mountains and Melones fault zones, which divide the metamorphic belt into three major structural blocks. Within each of the blocks, strata range in relative age from oldest on the west to youngest on the east. The major characteristics of the three structural blocks and the two fault zones are summarized in figure 3 (Clark, 1964).

Because deformation is most intense in the eastern block, it appears that the Calaveras Formation was intensely folded before the Cosumnes Formation was deposited (Clark, 1964). The fact that the older rocks of the eastern block are found in juxtaposition with younger rocks to the west indicates that the eastern block is upthrown. Thus, the metamorphic rocks in the eastern block probably were deformed at greater depth and under higher pressure than the rocks to the west (Clark, 1964).

Minor folds in the western metamorphic belt have been produced by two stages of regional deformation (Clark, 1964). They are largely steeply plunging, with axial planes which parallel slip cleavage and schistosity that is well developed on a regional scale. Cleavage is the dominant penetrative structure in the central and western block, and schistosity prevails in the eastern block (Clark, 1964). Lineations result from the alignment of elongate minerals or from the intersection of bedding and cleavage. They are most common in the rocks of the eastern block and within the two major fault zones. Regionally, lineations that show a consistent pattern are aligned in the direction of the b-tectonic axes of both deformations (Clark, 1964).

Most of the faults in the region are associated with the Melones and Bear Mountains fault zones, which, together, comprise the major elements of the Foothills fault system. Both fault zones have components of reverse or thrust movement as indicated by the presence of older rocks on the east or hanging-wall sides of the faults (Clark, 1964). Davis (1969) proposed that displacement along the faults was at least initially due to thrusting. Detailed study of steeply plunging lineations indicates that they are mostly b-lineations and, hence, that some strike-slip movement has occurred (Chandra, 1953; Baird, 1962). The amount of displacement is apparently of large magnitude, but corresponding features on opposite walls of the fault zones have not been located (Clark, 1960). Cataclastic structures and textures are common in the fault zones. Lineations generally plunge steeply to the southeast but some may plunge northeasterly. Most linear elements show little evidence of having been rolled or rotated but on close examination some do reveal "snowball" structure (Clark, 196C). Movement along the faults of the Foothills fault system began during the Late Jurassic and may have continued, at places, into the Early Cretaceous (Clark, 1964).

Age relationships of plutonic rocks to the fault zones are not consistent. At some places contact aureoles have been superimposed over planar and linear elements of the fault zones, indicating that intrusion followed faulting (Clark, 1960). However, Cloos (1932), in a paper to be discussed later, shows evidence for shearing in rocks of the batholith that points to pre-faulting or syn-faulting intrusion. In any case, most of the intrusive period in the Sierra outlasted the faulting, as shown by radiometric dating.

Ultramafic bodies are elongated parallel to the fault zones, and their emplacement is thought to have been controlled by the faults (Ferguson and Gannet, 1932). Field evidence supports this proposed relationship because some small untramafic bodies are confined to cataclastic zones, and also because some large bodies intrude rocks closely adjacent to the fault zones. Strong shearing of serpentinites suggests emplacement before cessation of fault movement. Untramafic bodies have not localized shearing, however, since in some areas the fault zones contain little or no serpentinites. In general, the ultramafics are found in the area of the Melones and Bear Mountain fault zones (Clark, 1964).

Synopsis of Paleozoic and Mesozoic Geologic History

During Paleozoic time the Sierra Nevada region was on or near the continental margin and was the location of the Cordilleran eugeosyncline. Possibly, the northern part of the region was involved in the Mississippian Antler Orogeny (Bateman and Wahrhaftig, 1966). Major structures began to develop in the Permian or Triassic during the Sonoma Orogeny, with additional deformation taking place throughout the Jurassic (Bateman, 1968). Sizeable thicknesses of volcanic material and eugeosynclinal-like sediment were deposited during the Late Triassic and Jurassic (Bateman and Wahrhaftig, 1966).

Near the end of the Jurassic, the principal folding of Upper Jurassic and older strata occurred in the western metamorphic belt; this severe disturbance is referred to as the Nevadan Orogeny. In the eastern and central Sierra, two episodes of folding appear to have preceded a third, the latter apparently taking place during the Nevadan event (Bateman, 1968). Another stage of deformation, probably postdating the principal folding in the Nevadan Orogeny, is best seen in the western metamorphic belt and is characterized by the development of slip cleavage and steeply plunging minor folds and lineations (Clark, 1964). During the Late Jurassic the Bear Mountain and Melones fault zones were formed, possibly by initial thrust displacement followed by strike-slip movement. Ultramafic rocks, predominantly serpentinite, were injected along these faults suggesting that fault penetration was to great depth, perhaps to the upper mantle (Clark, 1964).

Plutonic rocks of the Sierra Nevada batholith then were emplaced during the five intrusive epochs outlined previously (Evernden and Kistler, 1970). Late Cretaceous plutons were emplaced along the western edge of the present Sierra crest, Late Triassic and Early Jurassic plutonic activity occurred predominantly on the eastern side of the batholith, and Late Jurassic plutons intruded rocks in the area of the western metamorphic belt (Bateman, 1968).

Some Important Previous Work of Special Relevance to the Study of the Oakhurst Roof Pendant

The metamorphic complex of the southern western Sierra Nevada is comparatively unstudied geologically. An incomplete study begun in 1916 by J. Fred Hunter of the United States Geological Survey is the only work reported in the area of this thesis. However, studies by Cloos (1932), Baird (1962), and Best (1963) elsewhere in the southern western Sierra provide valuable background information.

Twenty miles to the north, near Mariposa (Fig. 1), Cloos (1932) studied the possible southerly extension of the Melones fault zone in the area where it is truncated by the granodiorite of the batholith. Here he was able to demonstrate a viscous stage, a stage of incipient solidification, and a solid stage of intrusion.

The viscous stage is characterized by flow structures in the area near the termination of the fault zone. These include schlieren of elongation and linear and platy parallelism of crystals and inclusions. With increasing distance from the locality of fault truncation, the intensity of foliation and flow structures decreases gradually until mineral parallelism is lost. On approaching the region of fault termination, lineations bend into the northwest-southeast trend of the fault zone (Cloos, 1932). During incipient solidification, faults and flexures developed conspicuous drag features which suggest upward movement of the hanging wall relative to the footwall of the fault zone (Cloos, 1932). The solid stage is typified by joints and fissures resembling feather or shear joints, both of which are attributed to movement between fault blocks. Near Mariposa, however, these features appear to have formed as a consequence of the movement of magma (Cloos, 1932). Thus, the Melones fault zone developed between the initiation of granodiorite intrusion and final solidification. The linear structures in the granodiorite suggest that the faults may not have terminated in the area of truncation, but extend an unknown distance to the southeast and are only obscured by the granodiorite in the vicinity of Mariposa (Cloos, 1932).

Still farther north, near Columbia (Fig. 1), Baird (1962) studied an area of deformed Calaveras rocks which lie directly east of the Melones fault zone. He reports two episodes of progressive metamorphism of greenschist and almandine-amphibolite facies, respectively, and a stage of retrogressive metamorphism represented by chloritization of biotite and amphibole. Also, he recognizes two generations of structures. The first is characterized by flexural-slip folding of original lithologic banding. These folds have steeply plunging axes and vertical axial-planes which strike in a direction normal to the trend of the Sierra Nevada. Fold-axis and axial-plane geometry and orientation suggest that these folds were superimposed upon a preexisting structure of regional extent, a feature which strikes approximately parallel to the Sierra. Later associated movement resulted in a well-developed foliation, subparallel to axial planes, which disturbed and locally obliterated original lithologic banding. Associated with this first deformational phase is the regional metamorphism of the almandine-amphibolite facies, which extends to the staurolite zone (Baird, 1962).

The second phase of deformation resulted in steeply plunging folds produced by laminar slip movement along surfaces parallel to the Mother Lode or Foothills fault system. Movement surfaces transect lithologic layering and the earlier-formed foliations. B-lineations generated during this second stage display a rotational geometry suggesting subhorizontal slip, and, therefore, a component of strike-slip movement along the Melones fault zone. This deformation was associated with regional metamorphism of the greenschist facies (Baird, 1962).

Best (1963) studied an area southwest of Mariposa, in Mesozoic rocks of the western structural block. He identified folds with strong axial-plane foliations which strike northwest and dip steeply northeast, parallel to regional

Sierran trends. The deformation which produced these folds was concurrent with regional metamorphism of the greenschist facies and is an expression of the classical Nevadan orogeny.

Post-tectonic granitic intrusion recrystallized the rocks under pressure-temperature conditions transitional between those of normal regional (almandine-amphibolite facies) and contact (hornblende-hornfels facies) metamorphism (Best, 1963).

Best and Baird provide valuable information about the structural and metamorphic history of this comparatively little studied region. From their work, as well as that of several other concurring authors, a hypothetical and generalized Late Paleozoic-Middle Mesozoic sequence of events may be outlined as follows:

F_1 →	F_2 →
M_1 →	M_2 →
Folds Normal to Sierra	Folds Parallel to Sierra, Associated With Faulting
Upper Medium Grade Metamorphism	Low Grade Metamorphism
Late Paleozoic	Middle Mesozoic

CHAPTER II

DESCRIPTION OF MESOSCOPIC STRUCTURAL AND LITHOLOGIC RELATIONSHIPS IN THE OAKHURST ROOF PENDANT

Lithology

Three lithologic units were distinguished and mapped in the study area. These will be referred to as the eastern unit, the central or hornblende schist unit, and the western unit. Contacts between the three units appear sharp with little or no suggestion of gradation. Near the contacts with surrounding batholithic rocks, the eastern and western units are coarsely crystalline and almost gneissose. Flow structure and boudinage are present at many localities. Minor folds in the contact zones appear to be related to the emplacement of the batholith. The contact between the hornblende schist unit and the granodiorite of the batholith is marked locally by a brecciated zone in which fractured blocks of the hornblende schist are enclosed by the granitic rock. Primary structures are obscured in the metamorphic units, original layering having been transposed by the development of an intense foliation (Fig. 4).

In addition to the delineation of the three metamorphic units and the plutonic masses, two northwesterly trending zones characterized by elongate bodies of two other rock

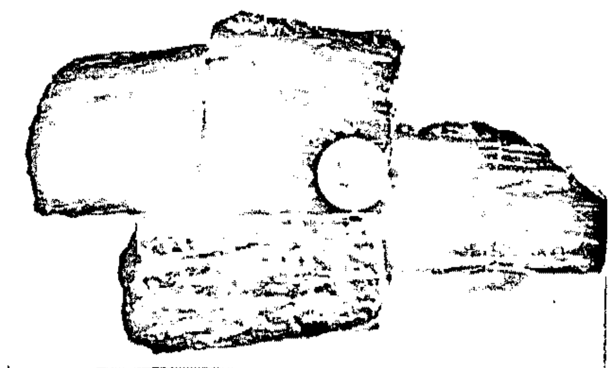


Figure 4. Photograph of four hand specimens that illustrate the transposition of early layered structures into the dominant plane of foliation observed in the rocks of the roof pendant.

types were mapped. One type consists of apparently sheared granitic rock, the other is ultramafic in character. Following is a brief description of the three major metamorphic units within the area and additional comments regarding the plutonic and "other" rocks. Detailed descriptions will be presented later.

Eastern Unit

The eastern unit is largely quartzitic but is occasionally interlayered with micaceous bands. Where the micaceous layers are prominant, the unit takes on a schistose appearance. Close to granitic contacts the rock becomes coarsely crystalline. Foliations in the unit have a synoptic dip of 78° northeasterly. Vertical dips are common, and some steep southwesterly dips are also present. The partial section studied in the pendant reaches a maximum outcrop width of 14,200 feet in the vicinity of Miami Mountain, located in the extreme northern part of the area (Plate 1).

Central Unit--Hornblende Schist

Field examination shows the central lithologic unit to be composed mainly of hornblende and quartz-rich rocks with little or no visible mica. It is blue-green and well foliated. Dips are to the northeast with the synoptic plane dipping at 64°; some, however, are vertical. As in the eastern unit, a few high-angle southwesterly dips occur. The rock varies from very fine grained to coarsely crystalline. Grain size increases markedly toward the interior of the unit where individual hornblende crystals may reach nearly a quarter of an inch in cross-section diameter. The hornblende produces a prominent lineation which is best expressed where the unit is fine grained but which is absent in outcrops of the coarsest material. The hornblende schist unit displays its greatest outcrop width of 6150 feet immediately southwest of Deadwood Peak, in the southern part of the area (Plate 1).

Western Unit

The lithology of this unit bears a noticeable resemblance to that of the eastern unit. It is dominantly quartzitic, with micaceous layers or bands, and becomes more schistose with an increase in mica content. It, too, is gneissose near igneous contacts. Generally well foliated, it displays an average northeasterly foliation dip of 40^{o}. The maximum width of exposure of 4525 feet is in the Indian Hill-Grub Gulch region, in the central portion of the roof pendant (Plate 1).

Plutonic Igneous Rocks

The major plutonic mass in the region is the granodiorite of the Sierra Nevada batholith. Near Coarsegold, in the southwestern corner of the study area (Plate 1), three small intrusive bodies are exposed. One of these is exceedingly small, but the others measure 3/4 by 1/4 to 1/2 of a mile. The two larger bodies differ in appearance. The more westerly is composed of fine-grained rock, which might be termed an aplite. The other intrusive body is compositionally similar to the main batholithic mass (granodiorite), but has an offshoot or branch that is more porphyritic. The smallest body, which is roughly circular, with an exposure width of no more than 1/4 of a mile, is identical in texture and composition to the rocks of the batholith.

"Other Rocks"

As mentioned previously, two northwesterly trends of elongate bodies of varying composition and appearance were mapped. One trend runs along the western flank of Potter Ridge and the other along the western flank of Buckeye Ridge and through the Grub Gulch region (Plate 1). The bodies are generally exposed over distances of less than a hundred feet along trend; their outcrop width is rarely greater than a hundred feet. Along both trends bodies composed of material that resembles sheared granitic rock crop out. These bodies are well foliated, strike northwesterly, and vary from almost white to a sandy or buff color. In addition, bodies crop out along both trends that are made up of material which appears to be of ultramafic composition. It is green or yellow-green in color and often is very soft and greasy to the touch, much like talc. Locally these rocks display distinct bladed crystals, suggesting possible contact metamorphic effects. Veins of fibrous asbestos or chrysotile-like material occur at a number of locales. The bodies are largely foliated, but some massive material also is present.

Structure

On a mesoscopic scale, a number of important structural features and relationships exist. Their geometry and mutual relationships will be described here, but interpretations will be deferred to Chapter IV. The most obvious of these features is the well-developed foliation which strikes northwesterly and dips northeasterly, parallel to regional Sierran trends. As indicated, the development of this foliation has apparently resulted in the transposition of older layered structures into the foliation planes (Fig. 4). Contoured Schmidt-net plots of poles to foliation planes in the western, hornblende schist, and eastern units, are shown in figures 5 A, B, and C, respectively. The maximum for each unit is shown in figure 5D. The latter figure illustrates fanning of foliations from gently dipping on the west to steeply dipping on the east. An isogonal map, contoured on the basis of equal dips of foliation

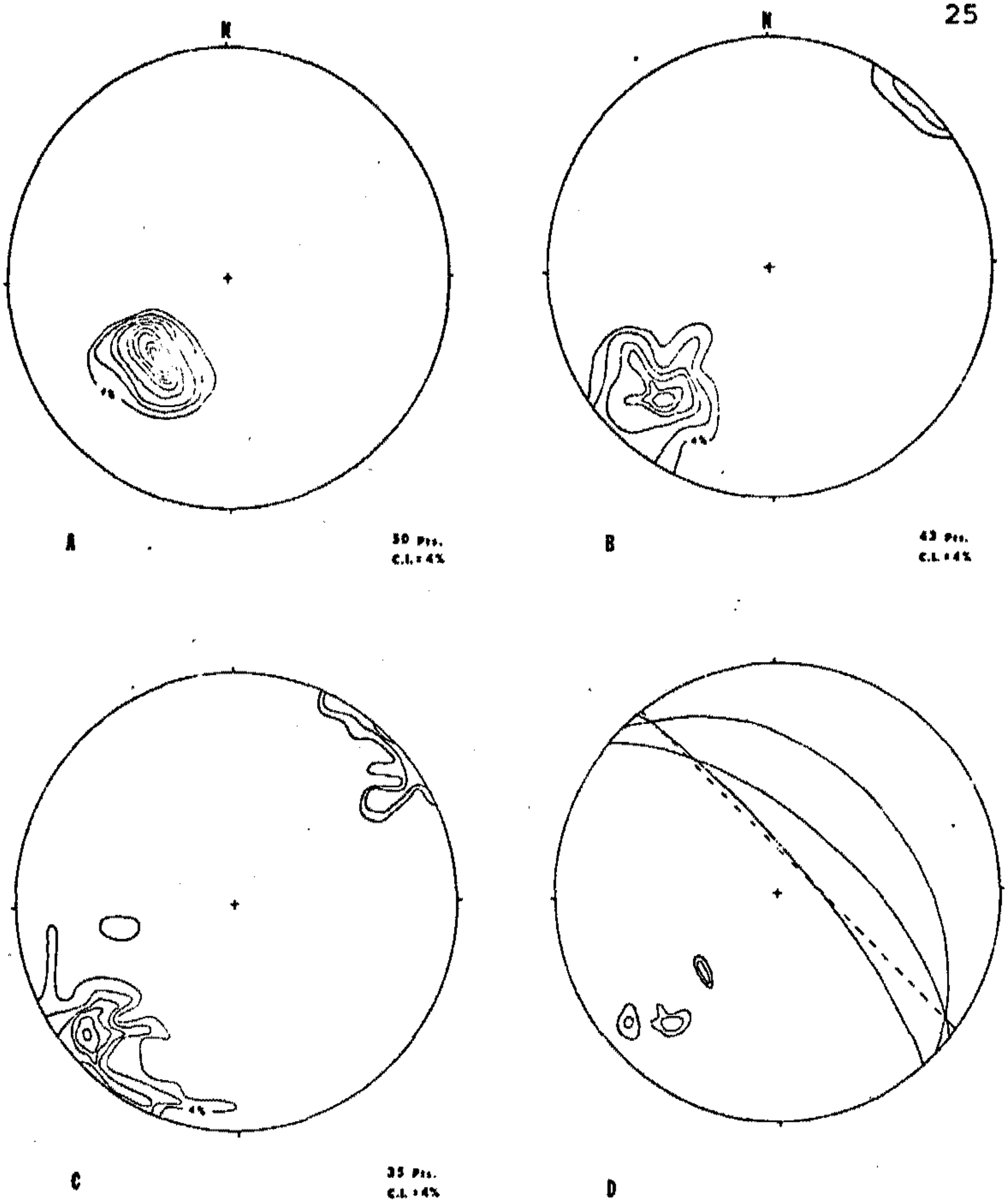


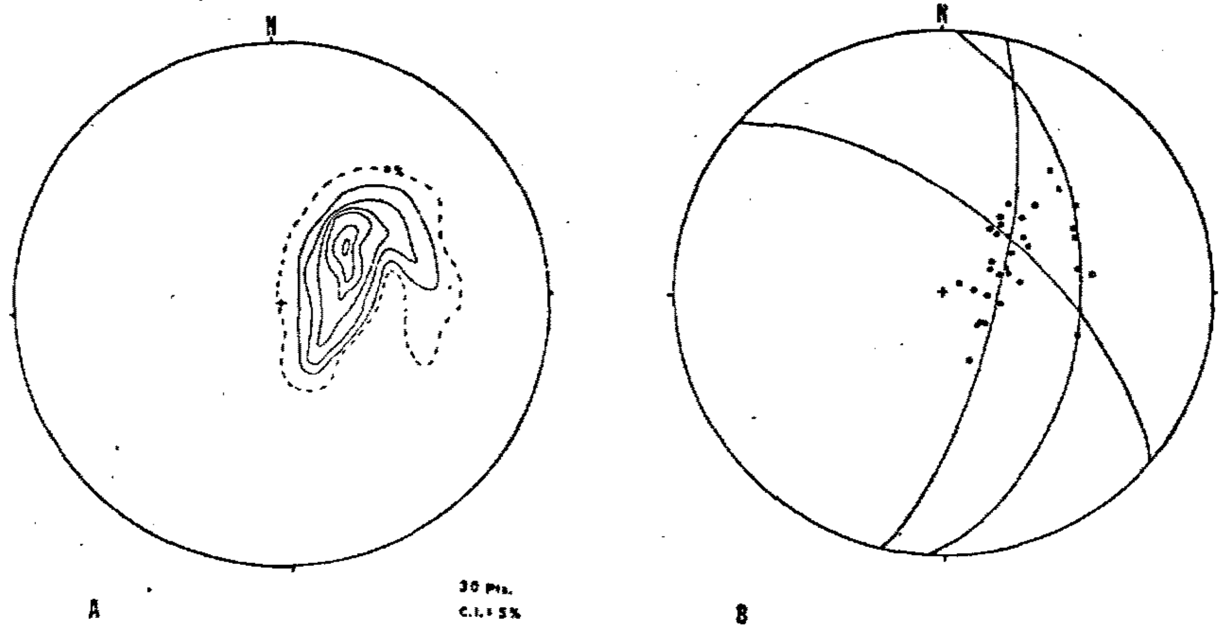
Figure 5. Contoured Schmidt net plots of foliations from the three units of the Oakhurst roof pendant. (A) Poles to foliation planes of the western unit. (B) Poles to foliation planes of the hornblende schist unit. (C) Poles to foliation planes of the eastern unit. (D) Contoured maxima for the three units. Great-circles depict the synoptic foliation plane for each unit; the dashed line represents the subhorizontal line defined by the intersection of the three synoptic planes.

planes, is shown in plate 2. Displayed, again, is the northwesterly trend, with a west to east steepening foliation fan. The foliations comprising the fan converge downward. Figure 5D displays synoptic foliation planes for each of the three units. It is apparent that these planes define a subhorizontal line of intersection.

Lineations in rocks of the roof pendant largely are confined to the hornblende schist unit. They result from the alignment of long, needle-like hornblende crystals. These lineations trend and plunge steeply in a northeasterly direction and are in, or lie close to, the foliation planes. Figure 6A is a contoured Schmidt-net plot of these hornblende lineations; figure 6B illustrates that the lineations fall on two great-circles which are subperpendicular to the synoptic foliation plane of the hornblende schist unit.

In the western unit lineations were observed at only three localities. These lineations are produced by the intersection of foliations with preexisting layered structures or by crenulations of the foliation planes themselves. When plotted on a net, these linear features fall on the easternmost great-circle defined by the hornblende lineations (Fig. 6B), thereby indicating a relationship between the two sets of lineations.

Mesoscopic minor folds are sparse in the rocks of the roof pendant. Where present, they display vertical or



A B

Figure 6. Schmidt net plots of lineation data. (A) Contoured net of hornblende lineations. (B) Hornblende lineations (dots) and western unit lineations (crosses) defining two northerly trending great-circles. Also shown in the northwesterly striking synoptic foliation plane for the hornblende schist unit.

near-vertical axes and steeply dipping axial planes of widely varying strike (Fig. 7). These folds are located chiefly in close proximity to igneous contacts, in rocks decidedly gneissose in appearance. In addition, they are associated locally with boudinage structures.

As described earlier, metamorphic rocks of the roof pendant are surrounded and partly intruded by the granodiorite of the Sierra Nevada batholith. The intrusive relationship with the metamorphics demonstrates that igneous activity was later than the penetrative tectonic event which produced the foliations. The age of this igneous activity has been determined radiometrically to be at between 98 and 136 m.y. ago, or Late Jurassic to Middle Cretaceous. Dated localities and their relationship to the pendant are shown below in figure 8:

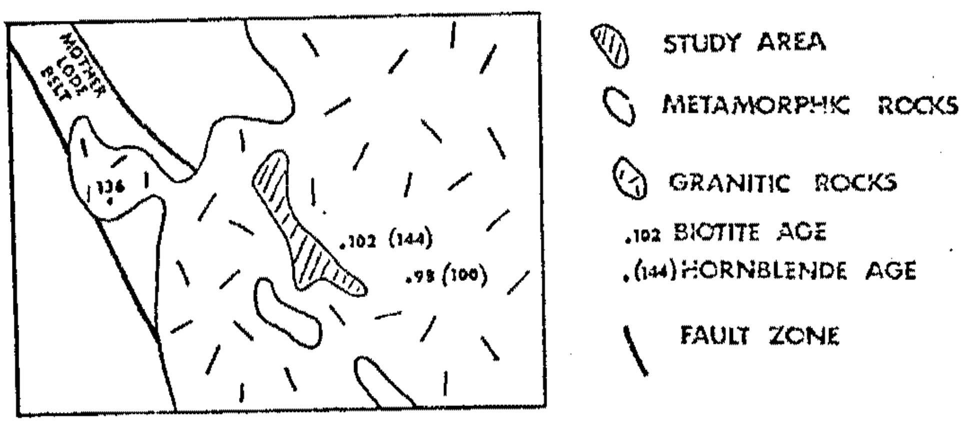


Figure 8. Index map of the geology immediately surrounding the Oakhurst roof pendant, showing locations of important radiogenic dates (after Evernden and Kistler, 1970).

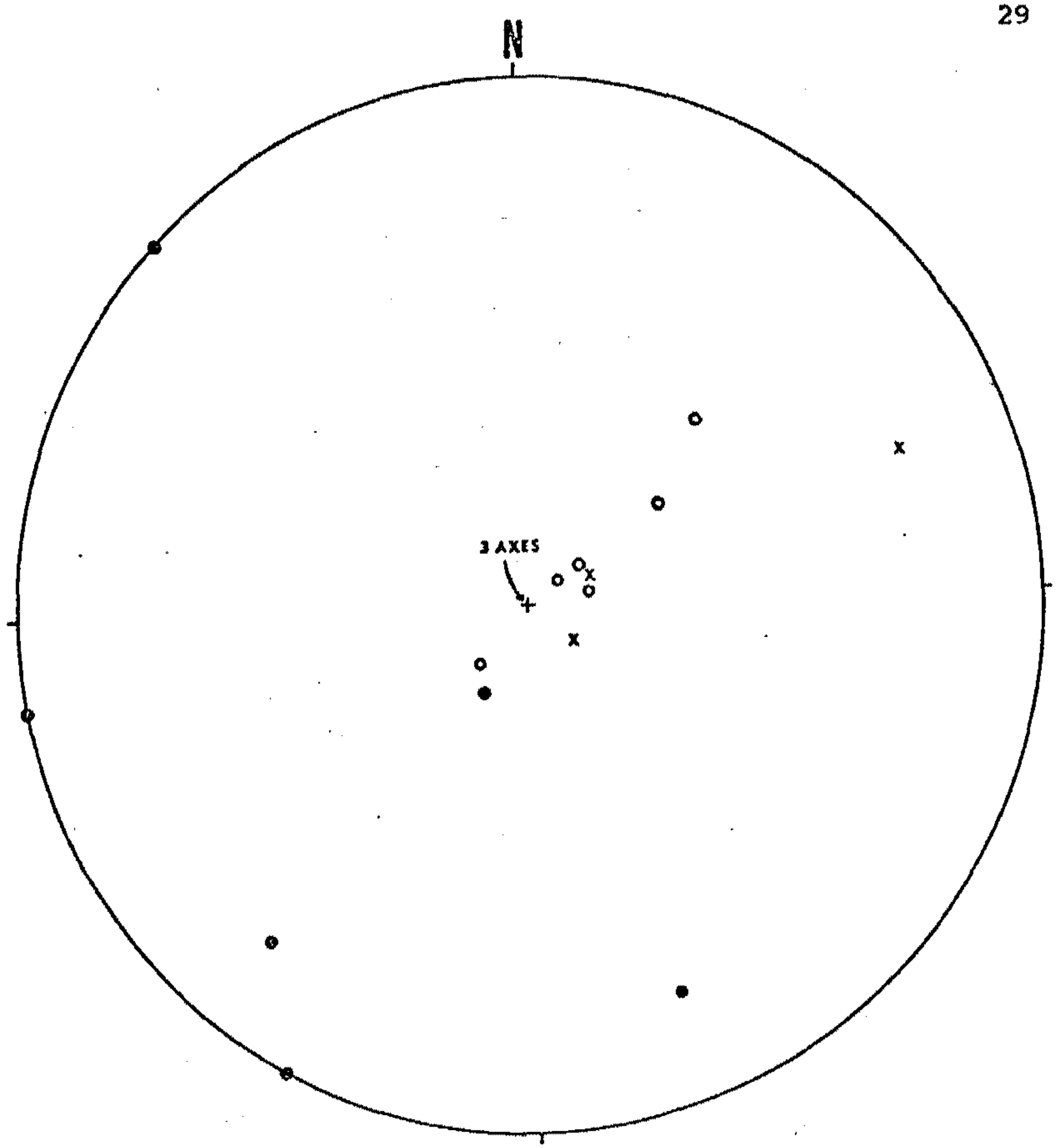


Figure 7. Schmidt net plots of minor fold axes and axial planes in rocks of the Oakhurst roof pendant. Crosses locate axes of mesoscopic minor folds; solid circles locate poles to their axial planes; open circles represent axes of minor folds identified microscopically but measured in hand specimen.

CHAPTER III

DESCRIPTION OF MICROSCOPIC MINERALOGICAL AND TEXTURAL RELATIONSHIPS

Following is a description of the mineralogical constituents and their textural relationships for each of the three metamorphic units making up the roof pendant, as well as for the rock bodies forming the two northwesterly trending belts.

Eastern Unit

Mineralogy

Mineral	Estimated Ave. %	% Range in Samples
Quartz	55%	25% - 75%
Muscovite	15%	5% - 35%
Sericite	15%	0 - 75%
Biotite	10%	0 - 25%
Plagioclase (An_{40-55})	5%	3% - 10%

Accessory Minerals: Sphene, tourmaline, chlorite, opaques.

Textures

Two dominant textures are visible in rocks of the eastern unit. The first of these is typified by the following features. Quartz and feldspars generally lack strain shadows and approach polygonal shapes. Micas are straight and often poikiloblastic, and sprays of sericite are common. In places these sprays appear to be pseudomorphs of earlier porphyroblasts. Sericite completely replaced the preexisting mineral, which may have been a feldspar. These textural characteristics suggest static recrystallization (Fig. 9).

A penetrative s-plane is present in eastern unit rocks but is poorly developed in places. Where poorly developed the s-surface is exemplified only by a general alignment of micas, but where highly developed it is expressed by well-oriented micas concentrated in thin layers. This s-plane represents the foliation observed on a mesoscopic scale. Micas, although straight and well crystallized, occasionally display jagged and shredded edges. In addition, concentration of micas into narrow bands appears to have been tectonically controlled. Thus, this s-plane appears cataclastic in origin.

In a few samples, small shear folds can be recognized in hand specimen. In thin section these folds are outlined by micaceous, sericitic, or quartzitic bands and have axial planes which parallel the s-plane (Fig. 10). Fold crests invariably appear stretched and elongated parallel to the s-plane, while fold limbs are often attenuated or thinned-out in the same direction. These minor folds apparently represent the incomplete transposition of preexisting layering into the plane of foliation. Measurements

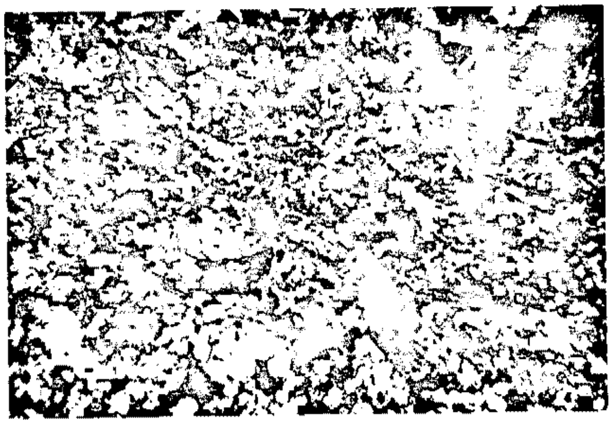


Figure 9. Photomicrograph illustrating static recrystallization in the rocks of the eastern unit. Note poikiloblastic micas (slightly blue). Approximate magnification 47x. Nicols crossed.

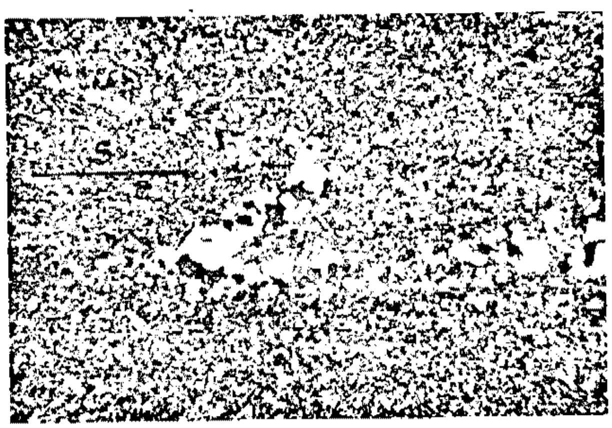


Figure 10. Photomicrograph of a shear fold in a quartz-rich layer from an eastern unit sample, illustrating that the fold axial plane parallels the foliation or <u>s</u>-plane here seen oriented horizontally across the picture. Approximate magnification 47x. Nicols crossed.

of the folds in hand specimens indicate that axes trend dominantly northeasterly and plunge steeply down foliation planes.

Central Unit - Hornblende Schist

Mineralogy

Mineral	Estimated Ave. %	% Range in Samples
Quartz	40%	25% - 50%
Hornblende	40%	25% - 50%
Diopside	10%	0 - 30%
Plagioclase (An_{36-46})	5%	0 - 10%
Epidote	3%	0 - 15%
Biotite	2%	0 - 25%

Accessory Minerals: Opaques and calcite (vein or vug filling).

Textures

In thin section, rocks of the hornblende schist unit display textures characterized by large porphyroblasts of hornblende and an s-plane defined by aligned hornblende fragments that flow around porphyroblasts. In addition, static mineral growth is suggested by such features as poikiloblastic textures.

The textural interrelation of hornblende and diopside is complex. Small crystals of hornblende and diopside occur within the large porphyroblasts of hornblende (Figs.

11 and 12). These inclusions show dominantly basal section views because thin sections were cut perpendicular to the s-plane and to hornblende lineations. At places the larger hornblendes lack these inclusions, but appear to have grown poikiloblastically over small quartz grains. Diopside apparently predates the growth of the large hornblendes since there is no textural evidence indicating contemporaneous crystallization. Diopside and hornblende inclusions do not form a perceptible pattern within the porphyroblasts, yet in some samples they appear sheared and fractured, possibly indicating that they were deformed cataclastically. The smaller hornblende crystals probably correspond to the steeply plunging, hornblende lineations identified as an important constituent of the mesoscopic fabric.

The most prominant textural feature of the hornblende schist unit is a well developed s-plane, which is the foliation observed in the field. This s-plane is defined primarily by small fragments of hornblende that are sheared off and flow around the large hornblende porphyroblasts (Figs. 12 and 13). Diopside, too, has been sheared, and small clasts are incorporated into the s-plane. Rarely, fine epidote fragments are aligned in the s-plane as well. Quartz and feldspar grains show some strain shadows developed during the penetrative deformation that produced the foliation. Where the deformation is most intense, quartz

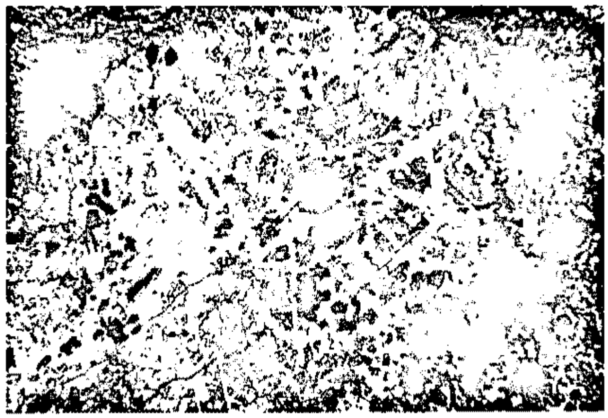


Figure 11. Photomicrograph of a hornblende porphyroblast with inclusions of diopside and hornblende. Approximate magnification 47x. Nicols crossed.

Figure 12. Photomicrograph of a hornblende porphyroblast surrounded by an s-plane which is defined by fragments of hornblende that flow around the porphyroblast. Note the inclusions of diopside within the porphyroblast. Approximate magnification 47x. Nicols out.

Figure 13. Photomicrograph of two hornblende porphyroblasts showing fragments cataclastically sheared or pulled from the porphyroblasts. Approximate magnification 47x. Nicols out.

and feldspar are broken down into small mortar zones which help define the s-plane. In some thin sections a possible second s-plane is suggested by the occasional alignment of small hornblende crystals in a northeasterly direction, across the major s-plane. If this is an s-plane, it is older than the dominant s which cuts and displaces it. All evidence presented in the above description of the major s-plane strongly suggests that it had a cataclastic origin.

Finally, a texture reflecting significant mineral recrystallization is recognizable in the rocks of this unit. All minerals show varying degrees of growth after major s-plane development. Quartz and feldspars are partially healed and largely without strain shadows. Hornblende and diopside show some recrystallization in the form of growth over fragments of other minerals. In some cases diopside displays a poikiloblastic texture, the included material being largely small quartz grains (Fig. 14). Epidote, too, has recrystallized, but its growth seems to have outlasted that of hornblende and diopside. This late growth is suggested by the tendency of epidote to envelope hornblende and diopside crystals and to grow at their expense. Biotite growth apparently also outlasts that of the other minerals. Biotite has grown along the cleavages of the hornblende crystals and, in places, largely replaces the hornblende (Fig. 15). The textures just

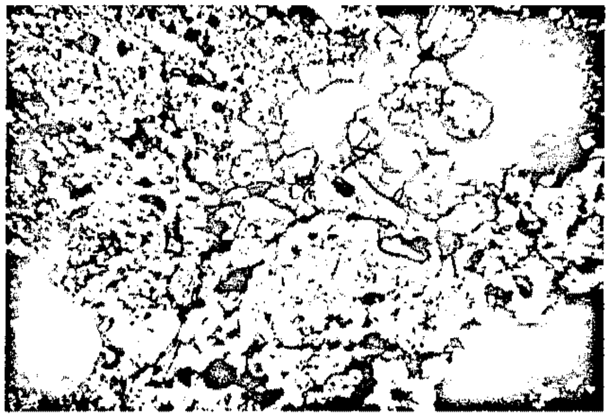


Figure 14. Photomicrograph of diopside poikiloblastically growing over quartz. Approximate magnification 119x. Nicols crossed.

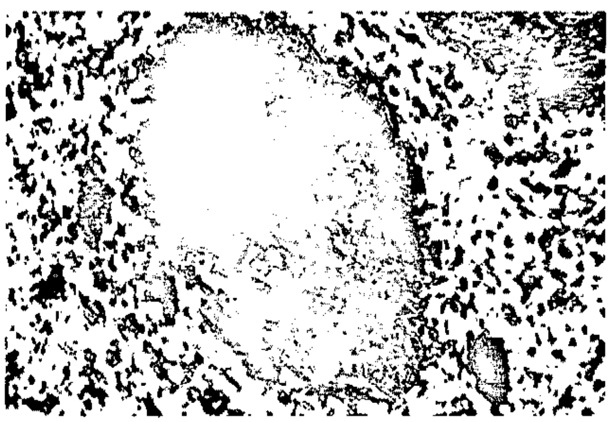


Figure 15. Photomicrograph of a large hornblende porphyroblast that has largely altered to biotite. Approximate magnification 47x. Nicols out.

discussed indicate an episode of static metamorphism. The thoroughness of attendant recrystallization is variable throughout the unit, and is nowhere complete.

Western Unit

Mineralogy

Rocks of the western unit are made up of the following two characteristic mineral assemblages:

Assemblage #1

Mineral	Estimated Ave. %	% Range in Samples
Quartz	55%	40% - 70%
Biotite	30%	20% - 40%
Muscovite + Sericite	8%	5% - 15%
Feldspar	4%	0 - 10%
Chlorite	3%	0 - 5%

Assemblage #2

Mineral	Estimated Ave. %	% Range in Samples
Amphibole	50%	40% - 60%
Quartz	40%	35% - 45%
Biotite	4%	0 - 20%
Diopside	3%	0 - 15%
Epidote	3%	0 - 40%

Accessory Minerals for Both Assemblages: Sphene, tourmaline, rutile, calcite, beryl, and opaques.

The amphibole present in the western unit is usually actinolite, but may be hornblende or actinolitic-hornblende. Diopside, when present, occurs as diallage, which displays a prominant 100 parting.

Textures

The textures of rocks comprising the western unit fall into two broad divisions. The first of these is characterized, as was the case in the hornblende schist unit, by alignment of amphibole fragments in an s-plane that flows around large porphyroblasts of amphibole. The second division shows characteristics typical of eastern-unit textures in that it is typified by an s-plane reflected in the concentration and alignment of micas. This s-plane outlines minor folds in places. Both of these two textural divisions include fabrics reflecting significant mineral recrystallization.

In rocks displaying characteristics of the second textural division, quartz and feldspar grains are largely unstrained and approach polygonal shapes. Micas are straight, and sprays of sericite are common. Chlorite is widespread, though not abundant, and appears to have grown at the expense of biotite. Both chlorite and sericite are late additions to the fabric as indicated by their superimposition on preexisting minerals and textures. The textural characteristics reviewed above suggest a phase of static recrystallization. An s-plane is present which, when best expressed, is characterized by long, linear zones in which micas, predominantly biotite, have been concentrated and aligned. However, in some cases it is defined only by a gross alignment of micas. This s-plane is the mesoscopic foliation mapped in the field. Micas in the foliation plane appear to be fractured or broken; quartz and feldspar in narrow mortar zones are aligned in the plane of foliation. These features suggest a cataclastic origin for the s-plane.

Occasionally, minor shear folds are well developed and outlined by micaceous bands. These folds have axial planes that parallel the dominant s-plane and crests that are thick and elongated in this foliation. What often appear to be folds are, in fact, converging, anastomosing shear zones. Nevertheless, throughout the western unit, a number of shear folds do occur. These folds, in all likelihood, represent shearing and transposition of earlier layered structures.

Rocks exhibiting characteristics of the first textural division have fabrics in which large porphyroblasts of amphibole, principally actinolite, are superimposed on, or envelope, small inclusions of amphibole and diopside (Fig. 16). These small inclusions often display basal-section views of the minerals (vertical view in thin sections cut perpendicular to s-plane). The later amphibole

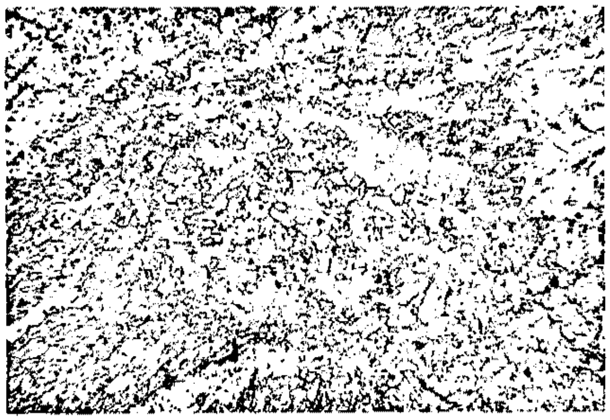


Figure 16. Photomicrograph of an actinolite porphyroblast displaying inclusions of diopside and actinolite. Note that the s-plane flows around the porphyroblast. Approximate magnification 47x. Nicols out.

porphyroblasts appear to be replacing diopside or growing at its expense. Occasionally the inclusions of amphibole and diopside within the large amphibole porphyroblasts appear to have been sheared and broken before porphyroblast growth. This texture may be a result of pre-porphyroblast cataclasis.

The amphibole porphyroblasts have had fragments torn from them, which are aligned in an s-plane or foliation that commonly is deflected around parent porphyroblasts (Fig. 16). Fine grains of biotite, diopside, epidote, and sphene, as well as mortar zones of quartz, are aligned in the s-plane. These are textures that imply cataclasis.

Finally, quartz and feldspar both approach polygonal configurations locally, and amphibole (possibly also diopside) display growth rims. Biotite, chlorite, and epidote appear to develop from hornblende and, in the case of the epidote, possibly from diopside. Chlorite growth outlasted that of biotite and, subsequently, took place at the expense of the biotite.

"Other Rocks"

In Chapter II (mesoscopic relationships) two northwesterly trending zones made up of isolated bodies of two rock types were discussed. One type appears similar to sheared granitic rock, the other to ultramafic rock.

Mineralogy

"Sheared Granitic" Rocks

Mineral	Estimated Ave. %	% Range in Samples
Quartz	60%	55% - 65%
Muscovite + Sericite	20%	15% - 25%
Plagioclase + Orthoclase	15%	5% - 35%
Biotite + Chlorite	5%	0 - 7%

"Ultramafic" Rocks

Mineral	Estimated Ave. %	% Range in Samples
Talc	35%	30% - 40%
Tremolite + Anthophyllite	35%	30% - 40%
Antigorite	25%	15% - 30%
Opaques	5%	0 - 10%

In the "sheared granitic" rocks biotite and chlorite occur in close association, and in the ultramafic rocks veins of sparry calcite are locally present. In the "ultramafic" rocks the estimated percentage for antigorite also includes minor amounts of other chlorite minerals, such as penninite.

Textures

The "sheared granitic" rocks display two major textural characteristics. The first of these is a well-developed northwesterly-striking s-plane, defined by the alignment of micas. A few mortar zones of quartz and feldspar are incorporated in the s-plane, with both minerals showing strain shadows. The mortar zones, strain shadows, and broken and sheared micas suggest that the s-plane is of cataclastic origin. In spite of apparent minor strain, quartz and feldspar have straight, polygonal grain boundaries. Micas are straight and some sericite sprays overgrow the foliation. Biotite, in many cases, is partially altered to chlorite. The above characteristics suggest static recrystallization.

In the rocks tentatively termed "ultramafic," antigorite and chlorite, in some cases, are aligned defining an s-plane striking northwesterly, but this alignment is largely obliterated by later and extensive mineral growth. Textures characterized by sprays of tremolite and anthophyllite which have overgrown antigorite and chlorite are common (Fig. 17). The amphiboles, in turn, are masked by the late growth of talc (Fig. 17), apparently contemporaneously with the development of veins of sparry calcite.

It might be noted that the two zones of "sheared granitic" and "ultramafic" rocks are associated with rocks

Figure 17. Photomicrograph of statically altered ultramafic rock, possibly originally serpentinite. Antigorite is the gray-white mineral; penninite is anomalous--blue; the mineral showing bladed or fan-like crystals is tremolite or anthophyllite; the dark regions along the upper and left hand borders of the photograph are dominantly talc. Approximate magnification 47x. Nicols crossed.

displaying greater cataclasis than do most of the rocks in the pendant. This is especially true in the hornblende schist unit.

CHAPTER IV

INTERPRETATION OF MESOSCOPIC AND MICROSCOPIC FABRICS

Mesoscopic Fabric

The earliest post-sedimentary event identifiable mesoscopically in the rocks of the Oakhurst roof pendant is defined by alignment of hornblende in the hornblende schist unit. Field observations show these lineations to be in or closely related to foliation planes of the unit. This close relationship suggests that lineation orientation may be controlled solely by the foliations. If foliations alone controlled lineation orientation, the two great circles on which the lineations fall would be perpendicular to the synoptic foliation plane for the hornblende schist unit. This relationship, however, does not exist, as shown in figure 6B. Therefore, these lineations are interpreted as defining an earlier foliation plane striking northeasterly, commensurate with the orientation of the two great circles. This early foliation will be referred to as $\underline{S}_1$; the event producing $\underline{S}_1$ is termed D_1. Subsequently, the lineations were incompletely transposed into the major foliation of the pendant, $\underline{S}_2$, a relationship which will be discussed later.

The presence of two great-circle trends, defined by lineations, may be interpreted in several ways. First, the eastern great-circle trend may result from lineations related to foliation planes with flatter dips and slightly different strikes than the majority. With this possibility in mind, the individual foliation planes containing the lineations on the eastern great-circle were rotated to coincide with the synoptic foliation plane of the hornblende schist unit. This rotation eliminates foliation orientation as a possible factor in determining the eastern great-circle trend. No substantial change in the dual pattern resulted. Second, the dual pattern may be the result of variations in the early foliation, $\underline{S}_1$. However, such variations seem unlikely, since the pattern observed is exceedingly regular. Third, the two great-circles may be a result of a north-easterly plunging fold system, with the two circles defining the limbs of sharp-crested folds. This hypothesis is the most attractive of the proposed explanations. The interpreted fold system will be termed F_1; F_1 folds were formed during D_1, the event which produced $\underline{S}_1$ foliations.

Because the rare lineations of the western unit fall on the eastern great circle, they are interpreted as being genetically related to the hornblende lineations. The same rotation was performed on the individual western unit foliations containing these lineations as was done in the case of the corresponding foliations in the hornblende schist unit.

Again, the rotation resulted in no substantial change in orientation.

The second major event apparent on a mesoscopic scale is represented by the conspicuous foliation of the region, $\underline{S}_2$. A cross section along line A-A' on the isogonal map of foliation dips (Plate 2) illustrates a downward converging foliation fan (Fig. 18). Such downward converging fans are indicative of antiformal structures (Turner and Weiss, 1963). The structure probably is nappe-like, judging from the westward asymmetry of the fan. The event producing this major fold structure is characterized by intense penetrative deformation which transposed earlier layered structures into the dominant foliation, $\underline{S}_2$ (Fig. 4). The major fold event is here termed F_2; the deformation producing F_2 and $\underline{S}_2$ is referred to as D_2.

Geometric relationships between the lineations which define $\underline{S}_1$, and $\underline{S}_2$ foliations suggest an interpretive kinematic framework for the deformation, D_2. Synoptic $\underline{S}_2$ foliation planes intersect along a subhorizontal line (Fig. 5D) which defines a geometric b-axis. The geometric a-axis, by definition, is perpendicular to b and, by convention, in the plane of $\underline{S}_2$. The contoured maximum of $\underline{S}_1$-hornblende lineations falls on the synoptic plane of $\underline{S}_2$-foliations of the hornblende schist unit, indicating that the lineations are largely, though incompletely, transposed into the plane

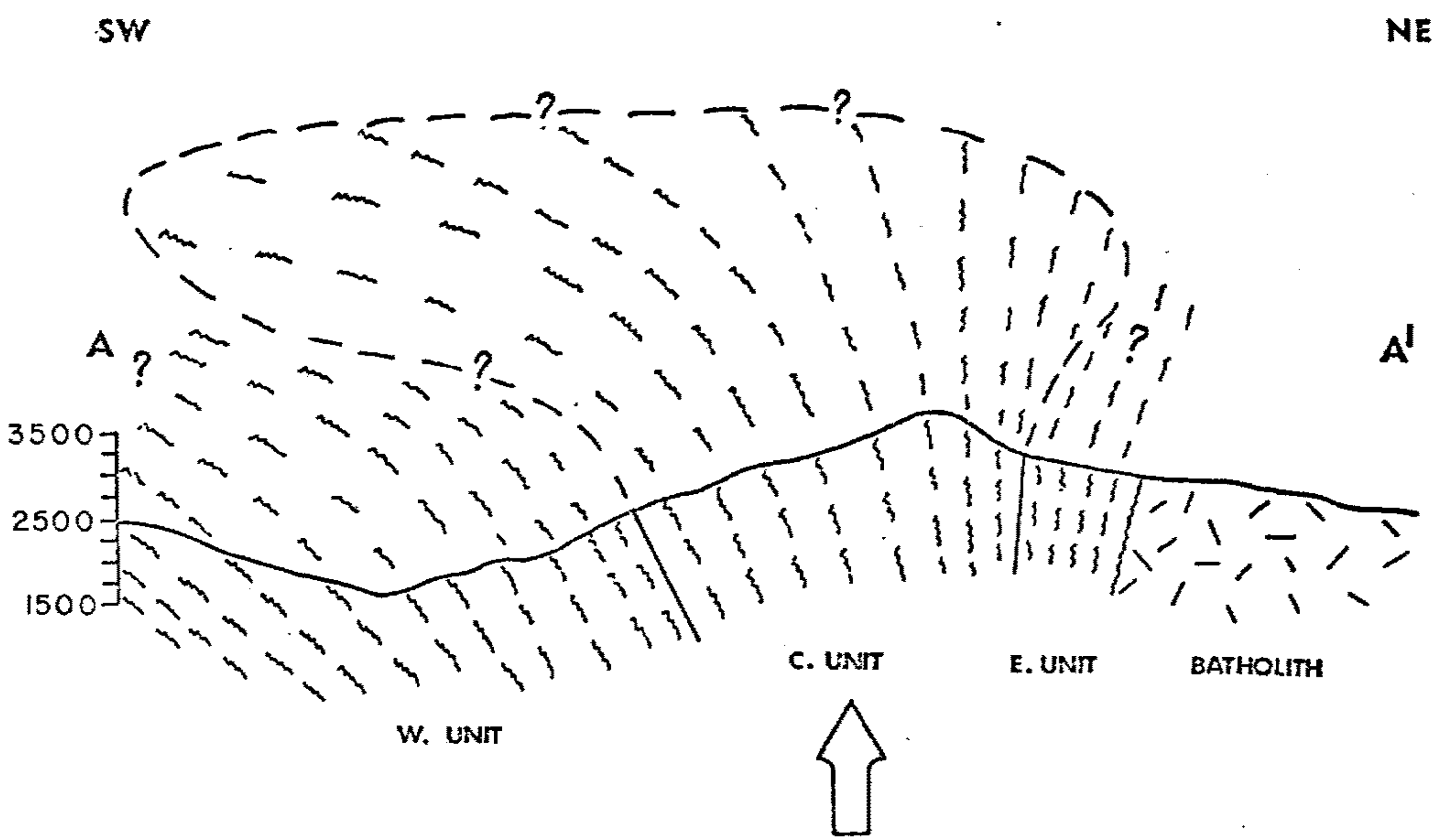


Figure 18. Generalized cross-section drawn along line A-A' on the isogonal map of foliation dips (Plate 2), illustrating the pronounced foliation fan and the interpreted antiform or nappe-like structure. The arrow indicates a suggested "regurgitation" or upwelling of material from a deeper structural level.

of $\underline{S}_2$ (Fig. 19). According to Turner and Weiss (1963), this relationship between a foliation and an earlier lineation indicates that the lineations not only were transposed into the foliation plane, but also that their orientation defines an a-kinematic axis for the deformation which produced the foliation. Therefore, the lineation maximum which concentrates on the synoptic plane of $\underline{S}_2$ foliations (Fig. 19), defines the a-kinematic axis of the deformation, D_2, which produced the $\underline{S}_2$ foliations. The steep plunge of this axis is anticipated because F_2, interpreted from the foliation fan, is a subhorizontal antiform. Furthermore, the axis is nearly perpendicular to the geometric b-axis defined by the subhorizontal line of intersection between foliations of the three units of the pendant (Fig. 5D). Because the interpreted a-kinematic axis is essentially perpendicular to the geometric b-axis, and, hence, parallel to the geometric a-axis, geometric and kinematic axes are coincident. $\underline{S}_2$ and F_2, then, are interpreted as resulting from a "regurgitation" or upwelling of material from a deeper structural level. That $\underline{S}_1$ lineations have not departed from their great-circle trends, despite transposition, indicates that the subvertical movement was nonrotational.

The last major event recognizable on a mesoscopic scale involves the intrusion of part of the Sierra Nevada batholith. The radiometric dates presented earlier

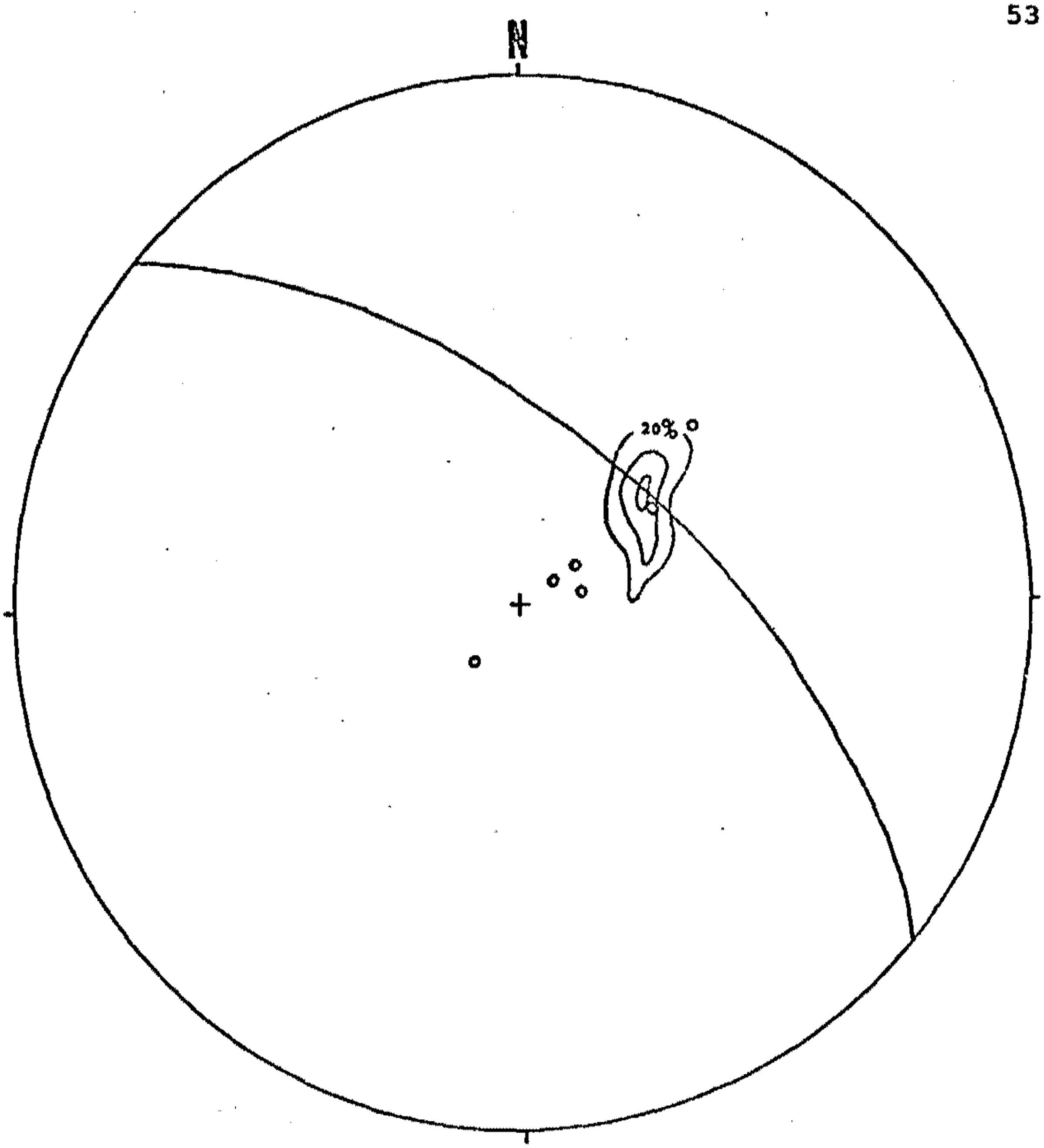


Figure 19. Schmidt net plot depicting the relationship of the synoptic foliation plane of the hornblende schist unit to the contoured maximum of hornblende lineations. Shown as open circles are the axes of minor shear folds identified microscopically and measured in hand specimen.

(Evernden and Kistler, 1970) show this intrusive event to be Late Jurassic to Middle Cretaceous in age.

The limited number of minor folds seen on a mesoscopic scale in the rocks of the Oakhurst roof pendant are consistently steeply plunging, but vary irregularly in axial-plane strike (Fig. 7). In addition they occur in gneissose rocks close to igneous contacts and, therefore, are probably genetically related to the process of igneous intrusion. For these reasons no important kinematic significance is assigned to these folds.

Structural characteristics of the two northwesterly trending zones defined by the bodies of "sheared granitic" and "ultramafic" rocks, are related to the mesoscopic fabric of the roof pendant. Foliations in the rock bodies defining these zones parallel the regional foliation, $\underline{S}_2$, thereby suggesting that both foliations were produced during the same penetrative event, D_2.

Microscopic Fabric

Mineralogy of the rocks of the Oakhurst roof pendant indicates that the original rock was sedimentary, probably an impure sandstone that at times was either dolomitic or pelitic. The resulting sedimentary rocks were exposed to three distinct metamorphic and structural events which are recorded in the microscopic rock fabric. The first of these is a complicated metamorphic event, hereafter referred to as M_1. It is characterized principally by an early episode of amphibole (Hornblende I and Actinolite I) and diopside (Diopside I) growth, and a later episode of static growth, in which amphibole porphyroblasts grew over and at the expense of earlier minerals. M_1 may include a cataclastic episode, as suggested by the apparent shearing and fracturing of amphibole and diopside inclusions within large amphibole porphyroblasts, but identification of this episode is uncertain. Therefore, two possible chronologies for M_1, one without a cataclastic episode and one with such an episode, are shown in figures 20A and 20B, respectively. Because cataclasis is poorly and only locally expressed, scheme A is favored.

The presence of diopside in the early episode of this metamorphic event indicates that M_1 was at least of upper-medium metamorphic grade. Plagioclase compositions, which commonly fall in the range An_{40-45}, support this estimate of metamorphic grade. Biotite and muscovite (Biotite I and Muscovite I), and epidote (Epidote I) also are associated with M_1, but epidote is evident only in the static phase. Thus, M_1, taken as a whole, reflects the upper epidote-amphibolite facies of regional metamorphism.

The second of the three major events is characterized by the development of a prominant *s*-plane. This *s*-plane is the dominant mesoscopic foliation, $\underline{S}_2$, formed during D_2.

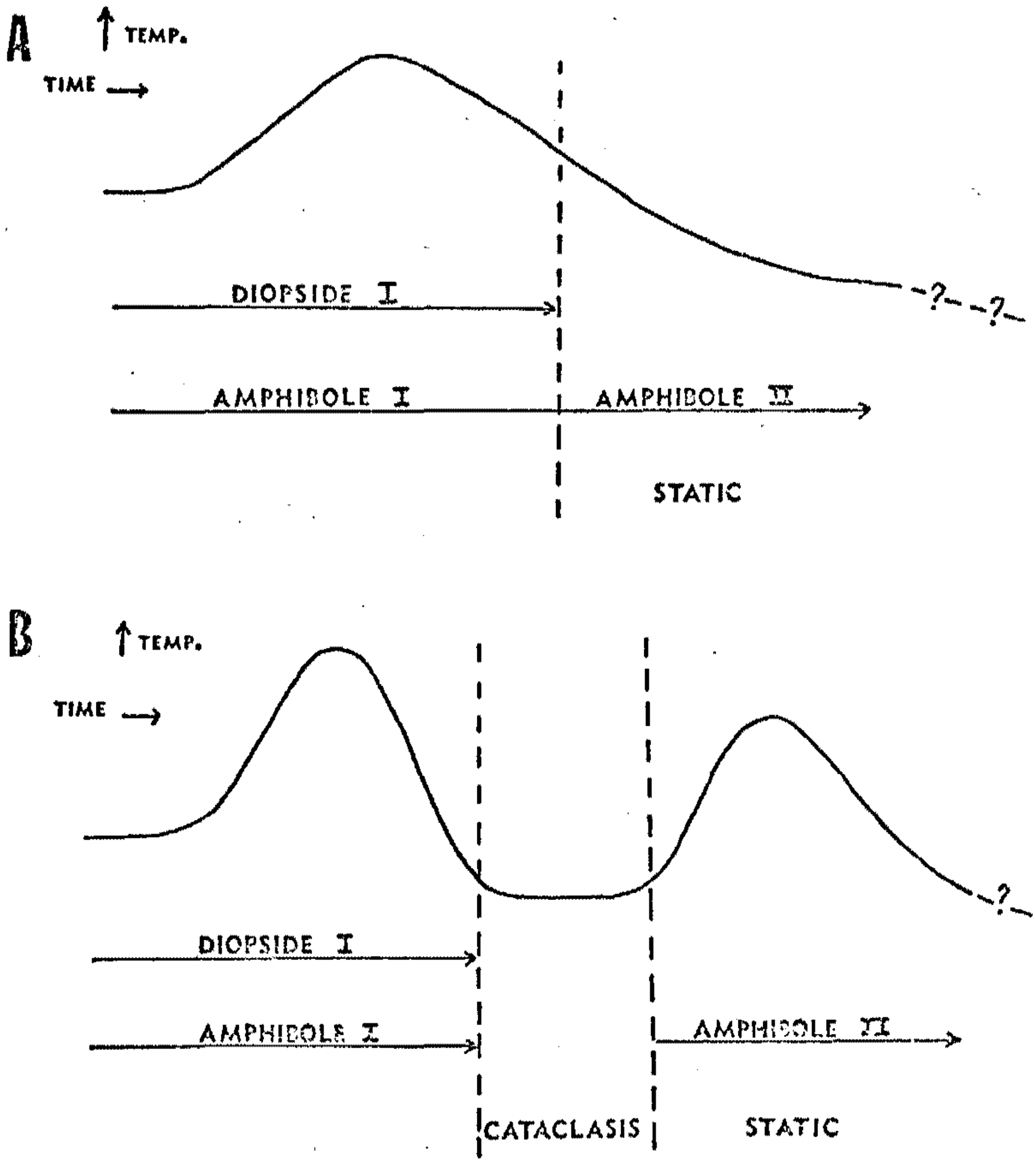


Figure 20. Alternative interpretive metamorphic histories for M_1. (A) Includes only one thermal peak. (B) Depicts two thermal highs separated by an episode of cataclastic deformation.

Foliation development is typified by the mechanical or cataclastic breakdown of amphibole porphyroblasts (Hornblende II and Actinolite II) and of micas, principally biotite (Biotite I), and the tectonic concentration and alignment of the resulting mineral fragments. The movement which invoked cataclasis also resulted in some minor folding of earlier layered structures, possibly $\underline{S}_1$. This early layering is considered, for two reasons, to be metamorphic in origin. First, the evidence just discussed supports the existence of an early metamorphism, M_1, of upper medium grade. Second, biotite, a fragile mineral when subjected to sedimentary processes, is a major, well-crystallized constituent of these layers. Structurally, the minor folds conform to the kinematic framework of the area, but further discussion of this topic will be temporarily postponed.

The third and final event interpreted from microtextural data is one of static metamorphism, here termed M_2. As described in the previous chapter, this event is characterized by recrystallization of existing minerals and the genesis of some others. Amphibole (Hornblende III and Actinolite III) and diopside (Diopside II) initially recrystallized at the peak of thermal activity, but yielded to the growth of biotite (Biotite II) and epidote (Epidote II), in many cases at the expense of the amphibole and diopside, under retrograde conditions. Some biotite, too, was affected during this retrograde episode, becoming partially chloritized (Chlorite I). These relationships are summarized in figure 21. Though initially characterized by locally high temperatures, the dominant grade of this metamorphic event is low.

M_1 is expressed differently in rocks of the three metamorphic units. In the quartzitic and pelitic eastern unit, M_1 is expressed by well-crystallized, metamorphic, biotite (Biotite I) which was aligned in $\underline{S}_2$ as a result of post-M_1 penetrative deformation. In the calcic hornblende schist unit, and in the calcic zones of the western unit, M_1 is expressed by the growth of amphibole and diopside followed by the static growth of amphibole porphyroblasts. However, in the more pelitic zones, rocks of the western unit display M_1 in much the same way as in the eastern unit. The differing expressions of M_1, therefore, are considered to be a direct result of compositional differences within the units, with the intricacies of the event displayed to a greater degree in more calcic rocks.

The microtextural fabric of the rock bodies which define the two northwesterly trending zones is consistent, both structurally and metamorphically, with the fabric of the three major metamorphic units of the roof pendant. Mineralogically, rocks making up one of the two types of

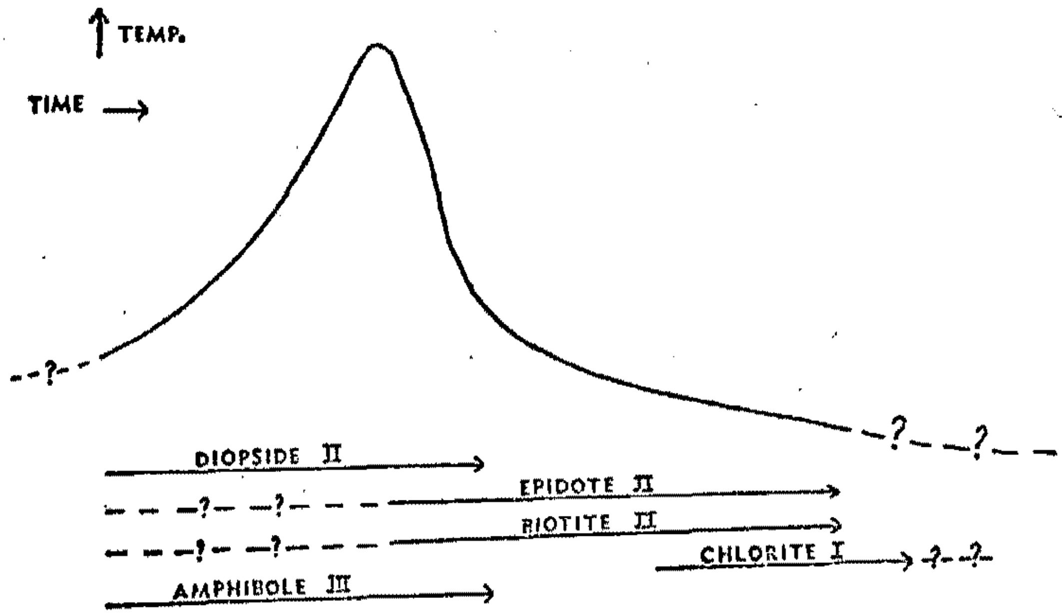


Figure 21. Interpretive metamorphic history for M_2.

bodies are compositionally similar to a silicic granitic rock. Although the feldspar percentage is relatively low in many samples, these rocks will be referred to as "sheared granitics," for the purpose of this discussion. Texturally, they display the last two of the three major events of the region. D_2 is manifested by cataclasis and the development of $\underline{S}_2$. M_2 is represented mainly by recrystallization of quartz, feldspar, and biotite, and in addition, by some retrogression of biotite to chlorite.

The mineralogy of rocks composing the "ultramafic" bodies is similar to that of metamorphosed serpentinites described by Pabst (1942). Texturally, these rocks display a static recrystallization that corresponds to M_2. The $\underline{s}$-plane defined by antigorite and chlorite alignment is $\underline{S}_2$, produced during D_2.

These ultramafic bodies probably were injected into the rocks of the pendant during D_2, possibly along fault zones. As mentioned, these zones largely correspond to areas of the most intense cataclasis in the hornblende schist and western units. Furthermore, they are aligned and on trend with the Foothills fault system to the north.

Relationship Between the Mesoscopic and Microscopic Fabrics and Chronologies

Thus far, the mesoscopic and microscopic fabrics have been treated separately; however, they are closely related and correlative both in chronologic development and orientation. A metamorphic event, M_1, is reflected on a microscopic scale by the early growth of hornblende I, the latter being the aligned hornblende of the mesoscopic fabric. Because the hornblende lineation distribution defines an early foliation, $\underline{S}_1$, the initial episode of M_1 probably was synkinematic.

The prominant mesoscopic foliation, $\underline{S}_2$, is the cataclastic s-plane revealed microscopically. Although genetically related to $\underline{S}_2$, the minor shear folds seen in thin section at first appear kinematically unrelated to this foliation, because of the steep plunge of their axes. Intuitively, these shear folds might be considered to be a product of horizontal or subhorizontal movement in the foliation planes, rather than of the subvertical movement that produced $\underline{S}_2$. Thus, the slight lateral dispersion of hornblende lineations on the Schmidt net could be attributed to the small component of horizontal movement accompanying the subvertical movement that produced $\underline{S}_2$. With this small horizontal component of movement, the minor folds could have been produced in the kinematic framework of $\underline{S}_2$. However, Davis (1969) stresses that shear-fold geometry cannot define unique kinematic axes. The relationship between fold axes and the a-kinematic axis of D_2 is shown in figure 19.

Lastly, the event of static metamorphism, M_2, represented microscopically by significant recrystallization of existing minerals, corresponds to the mesoscopic static-thermal event related to the intrusion of batholithic granitic rocks. As discussed earlier, M_2 was dominantly low grade, but was marked by locally higher temperatures. Therefore, M_2 took place largely under temperature-pressure conditions of the albite-epidote-hornfels facies, but locally under hornblende-hornfels facies conditions.

Figure 22 is a graphic representation of the relationship between the mesoscopic and microscopic fabrics and chronologies; it includes an interpretive and generalized thermal history. The interpretation omits the possible cataclastic event separating the inferred synkinematic and static phases of M_1.

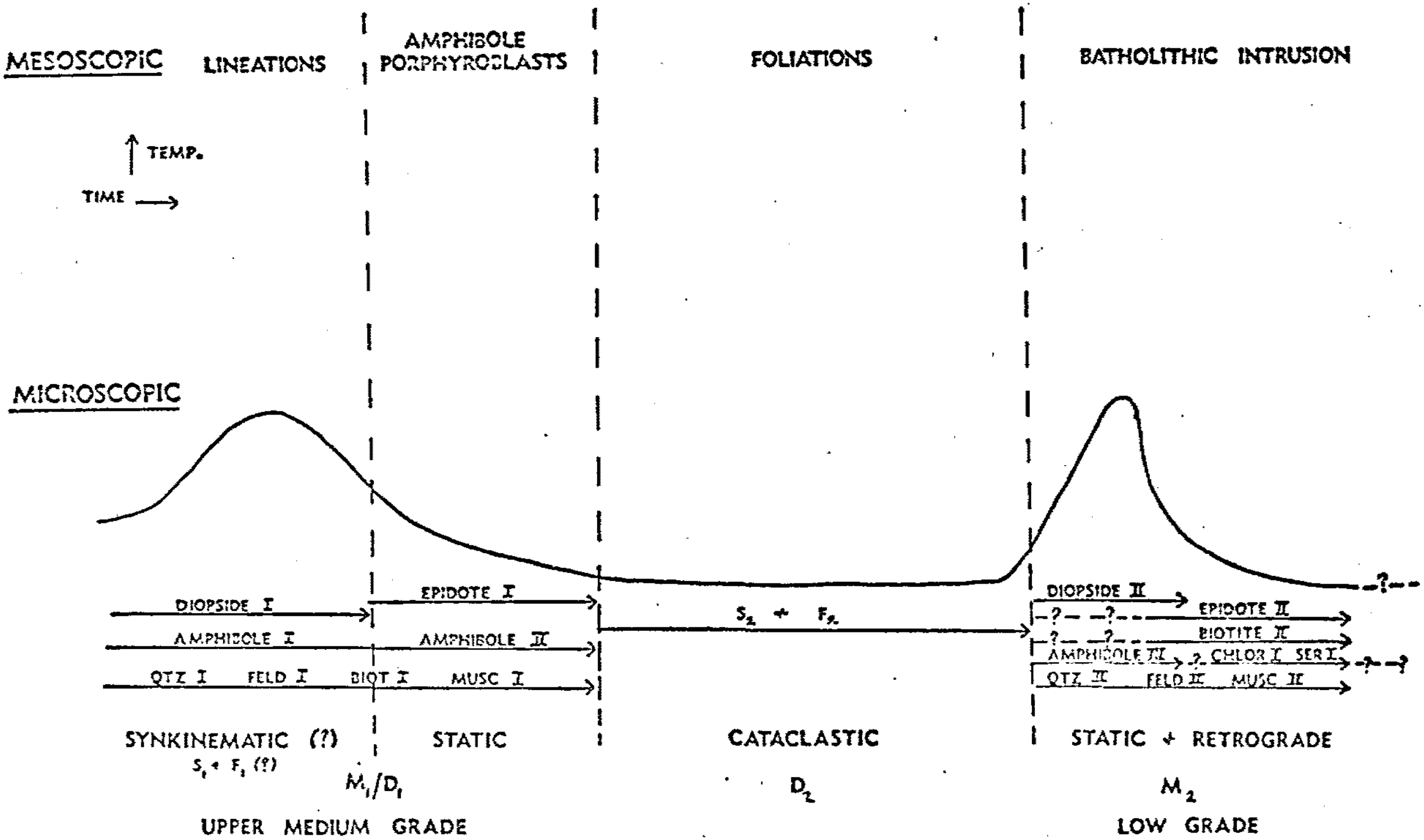


Figure 22. Synoptic diagram showing an interpretive metamorphic history for the Oakhurst roof pendant and the relationship between the mesoscopic and microscopic fabrics.

CHAPTER V

CONCLUSIONS, POSSIBLE REGIONAL SIGNIFICANCE, AND SUGGESTIONS FOR FURTHER STUDY

Conclusions

Study of the rocks of the Oakhurst roof pendant reveals that clastic sedimentary rocks were effected by three major structural and metamorphic events: M_1/D_1, D_2, and M_2. M_1/D_1 was a complex structural-metamorphic event that consisted of two, and possibly three, episodes. The first episode was of synkinematic metamorphism which produced foliation planes, $\underline{S}_1$, defined by a great-circle distribution of steeply plunging lineations. These foliations strike northeasterly, subperpendicular to the regional structural trend of the Sierra Nevada. The second episode is poorly defined and, therefore, tentative. It consists of a possible period of cataclastic deformation separating the two well-defined episodes of M_1, but, as indicated, evidence for this cataclasis is not conclusive. The third episode was one of apparent static metamorphism, reflecting the end of pentrative deformation but the continued growth of minerals under slightly lower temperatures. The two principal episodes of M_1 occurred under upper-medium grade conditions, in the upper epidote amphibolite facies of regional metamorphism.

The second major event, D_2, is characterized by cataclastic deformation resulting in the development of the prominant foliation, $\underline{S}_2$, which strikes northwesterly, parallel to regional Sierran trends. These foliations developed concurrently with a large, asymmetric antiform or nappe-like structure, F_2, produced by subvertical movement. This movement probably represents an upwelling from a deeper structural level. Possibly associated with D_2 was the emplacement of bodies of "ultramafic" and "sheared granitic" rocks. These bodies were probably injected along fracture zones which may represent the roots of thrust sheets. Furthermore, these zones may delineate an extension of Mother Lode Belt faulting 20 miles south of its presently recognized termination near Mariposa.

The third major event, M_2, was a period of static metamorphism associated with batholithic intrusion which differentially recrystallized rocks of the roof pendant. Locally, this event initially occurred at relatively high temperatures, but retrograde conditions soon prevailed. Thus, M_2 was dominantly of the albite-epidote-hornfels facies, but locally of the hornblende-hornfels facies. During this event, the "ultramafic" rocks, probably initially serpentinite, were altered.

The radiometrically determined age of the batholithic rocks in the area varies from 98-136 m.y. M_2, then, is

Late Jurassic to Middle Cretaceous, with M_1/D_1 and D_2 being pre-Late Jurassic in age.

Work by Baird (1962) in rocks considered to be of Late Paleozoic age ("Calaveras Formation"), and Best (1963) in Mesozoic rocks of the western structural block, suggests that rocks of the two ages might be differentiated on the basis of structural trends. The Late Paleozoic rocks studied by Baird display two dominant structural trends, one northeasterly and the other northwesterly, while the Mesozoic rocks studied by Best exhibit only the northwesterly trend. Therefore, the metamorphic rocks of the Oakhurst roof pendant may be as old as Late Paleozoic.

Possible Regional Significance

The three structural and metamorphic events delineated in this study are comparable in trend and metamorphic grade to those inferred by Baird farther north near Columbia. The northeasterly trending structures and upper medium grade metamorphism of the early event, M_1/D_1, may be a southerly expression of the Late Permian-Early Triassic Sonoma Orogeny of Nevada; D_2, defined by the northwesterly trending foliations, $\underline{S}_2$, and major fold structure, F_2, reflects the deformation associated with the classical Nevadan Orogeny. M_2, the event of lower grade static metamorphism, corresponds to late-orogenic or post-orogenic granitic intrusion.

Plate tectonic theory suggests that a large piece of the western continental margin of North America was rifted away during the early Mesozoic (Hamilton, 1969; Burchfiel and Davis, 1972). This rifting resulted in the truncation of the Paleozoic northeasterly structural trends, which parallel the Late Paleozoic continental margin, and in the development of northwesterly trending structures paralleling the newly formed Mesozoic continental margin (Hamilton, 1969; Burchfiel and Davis, 1972). The structural trends which developed as a result of these events largely coincide with those inferred in the present study. Thus, the superposed structural trends exhibited in the Oakhurst roof pendant may have developed as a consequence of Mesozoic truncation of Late Paleozoic structures and the subsequent development of Mesozoic structures along a converging plate boundary.

Suggestions for Further Study

Many problems remain in the western Sierra Nevada. Several studies, possibly of great significance, are listed below as guides to further work:

(1) Investigation of the extent of the northeasterly trend and its relationship to the Sierran trend. Some such studies are presently in progress.

(2) Study of the regional significance of the northeasterly trend, should it prove to be of regional extent.

(3) Structural studies of the batholithic rocks between Mariposa and the area of this study, in order to assess the possible southern continuation of the Foothills fault system suggested here.

(4) Microtextural work in other areas of the western Sierra, designed to determine the complexities and extent of the early upper-medium grade metamorphism identified in this study and, previously, by Baird (1962).

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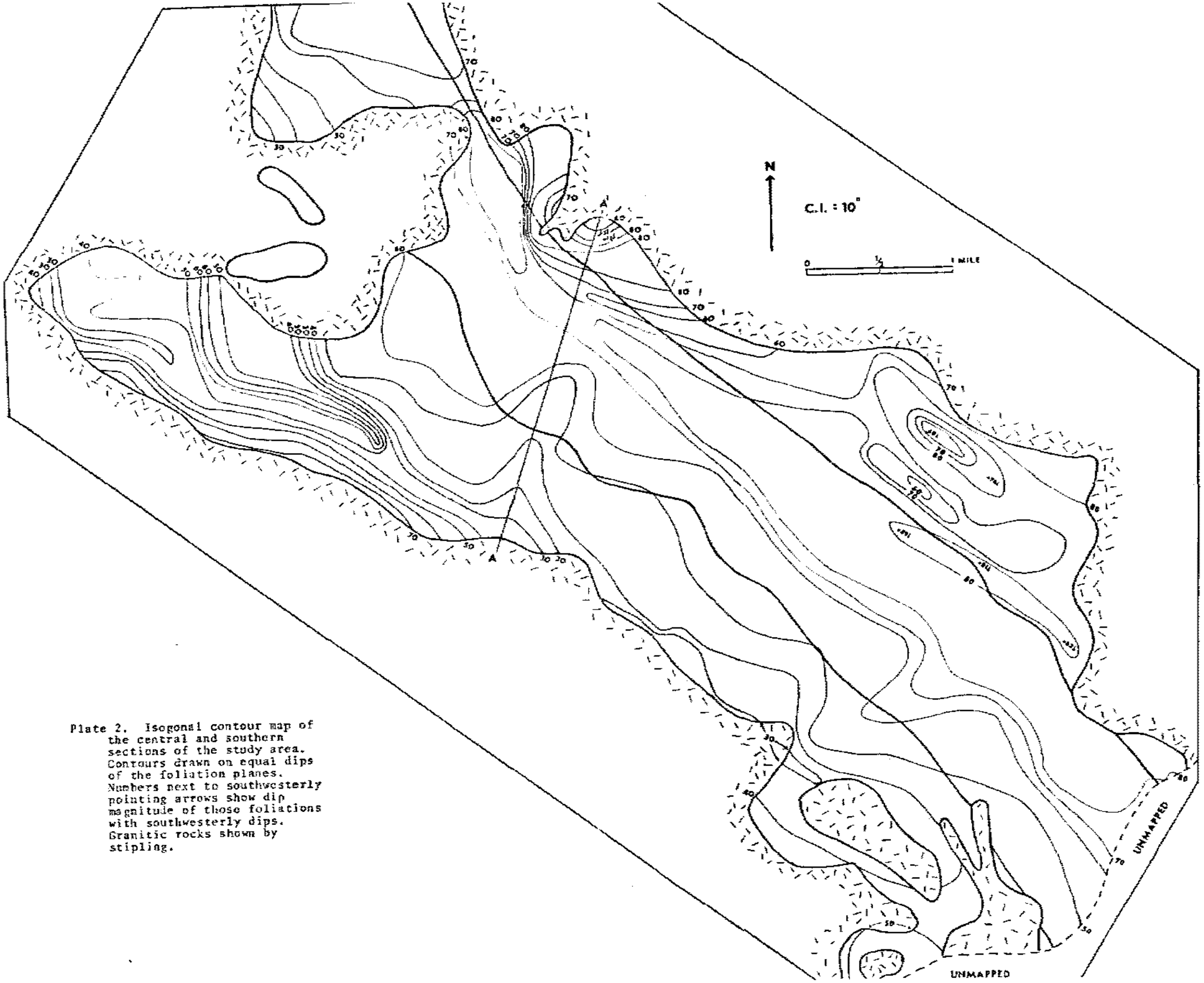

Plate 2. Isogonal contour map of the central and southern sections of the study area. Contours drawn on equal dips of the foliation planes. Numbers next to southwesterly pointing arrows show dip magnitude of those foliations with southwesterly dips. Granitic rocks shown by stipling.