

Petrologic and Structural Studies
in the Northwestern Sierra Nevada,
California

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1226



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Geology west of the Melones fault between the
Feather and North Yuba Rivers, California *By Anna Hietanen.*

The Feather River area as a part of the
Sierra Nevada suture system in California *By Anna Hietanen.*

Extension of Sierra Nevada-Klamath suture system into
eastern Oregon and western Idaho *By Anna Hietanen.*

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Geology West of the Melones Fault Between the Feather and North Yuba Rivers, California

By ANNA HIETANEN

PETROLOGIC AND STRUCTURAL STUDIES IN THE NORTHWESTERN SIERRA NEVADA

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1226-A

Petrologic and structural study
of metamorphic rocks within
a major structural belt



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GEOLOGY WEST OF THE MELONES FAULT BETWEEN THE FEATHER AND NORTH YUBA RIVERS, CALIFORNIA

By ANNA HIETANEN

ABSTRACT

Petrologic and structural studies on the area extending from Downieville on the North Yuba River to the Middle Fork of the Feather River provide additional information on metamorphic complexes within and west of a relict (Paleozoic and Mesozoic) subduction zone, the Melones fault. The study area joins the Bucks Lake, American House, and Strawberry Valley quadrangles on the west and is bounded by the Melones fault on the east. Three new chemical analyses together with thirteen analyses published previously confirm the earlier concept that metavolcanic rocks, designated the Franklin Canyon Formation, have chemical characteristics and a trace element content of an early island-arc-type tholeiite and andesite-sodarhyolite suite. A belt consisting of metachert and phyllite derived from sediments typical on ocean floors, and continuous with the Calaveras Formation to the west, is exposed between the Melones fault and rocks of the meta-andesite suite. Conodonts in interbedded limestone were dated as ranging from Pennsylvanian to Permian age in this part of the Calaveras Formation. The Pennsylvanian age for the Calaveras is confirmed by a 248-m.y.-old (Permian) amphibolite that intrudes these rocks. The metasedimentary rocks east of the fault are continentally derived shelf-type orthoquartzite and schist of the Silurian Shoo Fly Formation. The Melones fault thus separates continental rocks on the east from oceanic rocks on the west. The island arc developed some distance from the shore and was carried eastward during continued subduction along the Melones fault. A 285-m.y.-old gabbro along this fault zone suggest Paleozoic igneous activity. The volcanism in the island arc (the Franklin Canyon Formation) was a result of development of a late Paleozoic and early Mesozoic subduction zone west of the island arc. The southern part of the Franklin Canyon Formation is overlain by Triassic metasediments and intruded by a 160-m.y.-old gabbro. Metamorphism in most parts of the study area was in the border zone of the greenschist and epidote-amphibolite facies. Crossite, pumpellyite, lawsonite, and stilpnomelane preserved in a lens-shaped intricately deformed slice of Calaveras-type rocks within the Melones subduction zone west of Downieville indicate higher pressures and lower temperatures of recrystallization.

Introduction

Petrologic and structural studies on metamorphic complexes within and west of a relict subduction zone, the Melones fault, were begun in the Pulga and Bucks Lake quadrangles (Hietanen, 1973a) and later continued southward to the area around the North, South, and Middle Forks of the Feather River (Hietanen, 1976, 1977) and eastward to the vicinity of Onion Valley, La Porte, and Downieville. This report covers the La Porte 7½-minute quadrangle, most of

the Goodyears Bar and Onion Valley 7½-minute quadrangles, and the westernmost parts of the Mount Fillmore and Downieville quadrangles (fig. 1). The Melones fault forms the eastern border of the area. The total area mapped and studied in detail from the beginning of the work is about 2,500 km² between lat 39°30' and 40°01' N. and long 120°50' and 121°30' W.

Most of the rock units and the major faults are continuous with those in the Bucks Lake, American House, and Strawberry Valley quadrangles to the west. A large body of ultramafic rocks exposed between the Melones and the Rich Bar faults attains a width of 6 km in the central part of the Onion Valley quadrangle; in the southern part of the quadrangle, it narrows down and terminates under the Tertiary pyroclastic rocks. Long narrow bodies of ultramafic rocks accompany the various branches of the Melones fault in the southern part of the study area. Hornblende in associated gabbro yielded a potassium-argon age of 285 m.y.

The amphibolite exposed in the northeastern part of the La Porte quadrangle and the southern part of the Onion Valley quadrangle is Permian (248 m.y.). It is basaltic in composition but differs in its structure, texture, and circular outline from the metabasalts and their plutonic equivalents, the meta-gabbros that are common elsewhere in the study area. The amphibolite is bordered by basaltic meta-tuff on the south, west, and northeast and is cut by the Melones fault in the east. Metasedimentary rocks similar to the Shoo Fly Formation occupy its central part and are wedged between its northeastern part and the Melones fault.

A belt of metachert, phyllite, and minor limestone on the west side of the Melones fault is continuous with the Calaveras Formation in the Bucks Lake quadrangle now dated as Pennsylvanian. The next belt to the west consists of potassium-poor early island-arc-type metavolcanic rocks mapped as the Franklin Canyon Formation. Dogwood Peak fault, which separates these two formations in the Bucks Lake quadrangle, continues through the La Porte quadrangle into the northern part of the Goodyears

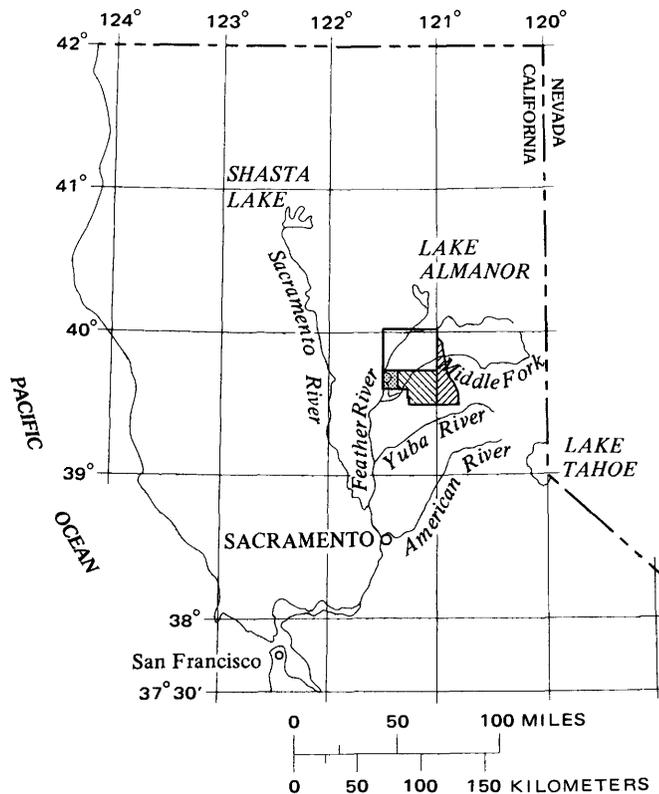
Bar quadrangle, where it disappears under Tertiary pyroclastic cover. It probably joins the Ramshorn fault, which, south of the pyroclastic cover, separates the Calaveras Formation east of it from the Triassic metasedimentary rocks in the southwestern part of the study area.

Ferguson and Gannet (1932, pl. 3) mapped several members in the Calaveras Formation in the Colfax quadrangle, which joins the Goodyears Bar and Downieville quadrangles in the south, and extended the contacts to the North Yuba River. Their sepa-

ration from the Calaveras of the metavolcanic Tightner Formation just west of Downieville, and of the overlying mainly metasedimentary Kanaka Formation and Cape Horn Slate, is not feasible in the Present study area. Rather, the Calaveras Formation here consists of interbedded metachert and phyllite and includes discontinuous layers and lenses of metavolcanic rocks.

The largest of the lens-shaped masses of meta-volcanic rocks within the Calaveras Formation is the meta-andesite south of Morrystown Ravine. This mass occupies a synclinal area and seems less deformed than the rocks of the Calaveras Formation. Diabase and associated pillow basalt are exposed on Reese Ravine and on the headwaters of Old Mill Creek.

The Tertiary extrusive rocks that cover the higher parts of most ridges are similar to those in the neighboring quadrangles to the west (Heitanen, 1972, 1973a). The oldest formation, the Miocene Lovejoy Basalt (Durrell, 1959; Dalrymple, 1964), is exposed in the Onion Valley quadrangle and in the vicinity of Little Grass Valley Lake. Pyroclastic andesite, mainly mudflow breccia, forms long north-east-to-southwest-trending ridges. In many places, Eocene gravels underlie these rocks; they have been extensively mined for gold. The youngest rocks, olivine basalt and platy andesite, form cones and pluglike bodies, many of them capping hills that rise above the pyroclastic andesite.



EXPLANATION

-  Area of this report (see plate 1)
-  Area of U.S. Geological Survey Professional Paper 1027 (Hietanen, 1977)
-  Area of U.S. Geological Survey Professional Paper 920 (Hietanen, 1976)
-  Area of U.S. Geological Survey Professional Paper 731 (Hietanen, 1973a)

FIGURE 1.—Location of study area in northern California.

MAJOR FAULT ZONES

The Melones fault zone at the eastern border of the mapped area (pl. 1) is a major suture that separates the continentally derived blastoclastic quartzite and schist of the Silurian Shoo Fly Formation on the east from the metachert and phyllite of the Pennsylvanian Calaveras Formation on the west. This fault zone, in places 8 km wide, is made up of several faults with intervening slices of mantle-derived ultramafic rocks, small masses of 285-m.y.-old gabbroic and dioritic rocks, and neighboring metamorphic rocks. The easternmost branch of the fault zone, probably a continuous shear surface, even where partly covered by Tertiary volcanic rocks, is labeled the Melones fault on the map (pl. 1). Among the metamorphic rocks within the fault zone is a lens-shaped body of highly contorted quartzite and schist interbedded with discontinuous layers of metabasalt and meta-andesite that contain the low-temperature—medium-pressure facies minerals crossite, lawsonite, pumpellyite, and stilpnomelane. This lens, which has a tectonic style typical of trench melange (fig. 2A), is

exposed between the Melones fault and the Goodyears Creek fault west of Downieville and extends 13 km to the north, east of Saddleback Mountain, where

it consists mainly of highly contorted thin-bedded quartzite and schist (fig. 2B). Lithologically, this lens is similar to the Calaveras Formation but was intensely deformed and recrystallized at low temperatures when dragged down to higher pressures during the subduction of the marginal ocean basin. In structural contrast, the blastoclastic quartzite and schist of the Shoo Fly Formation on the east side of the Melones fault shows large folds and only a minute wrinkling, mapped as lineation.

The largest ultramafic body within the Melones fault zone, informally called the Feather River ultramafic body, extends northwest through the Onion Valley 7½-minute quadrangle to the Bucks Lake 15-minute quadrangle (Hietanen, 1973a). It is 6 km wide in the central part of the Onion Valley quadrangle but wedges out at its southern border. The southernmost exposure of this large ultramafic body, about 1 km wide, is along the South Fork of the Feather River where it is bordered on either side by amphibolite. A slice of Shoo Fly quartzite and schist is exposed between the amphibolite and the Melones fault. Thin, 0.5- to 1-km-wide slices of ultramafic rocks accompany the various branches of the Melones fault to the south. The largest of these, a long thin body of serpentine, lies along Goodyears Creek, extending from the North Yuba River to Poker Flat at Canyon Creek and presumably still farther north to Onion Valley, much of it covered by Tertiary volcanic rocks. On the west, the Goodyears Creek fault separates this body from the Calaveras Formation. The contorted low-temperature—medium-pressure metamorphic rocks lie east of this serpentine and are separated by the Melones fault proper from the Shoo Fly Formation on the east; only small lenses of serpentine occur along the easternmost branch of the Melones fault in the Downieville quadrangle. On the Chico sheet of the Geologic map of California (Burnett and Jennings, 1962), the Melones fault is shown along the Downie River, but the rocks on the western slope of this river are part of the Shoo Fly Formation and the fault is at the headwaters of its western tributaries, continuing north on the east side of Fir Cap. A small lens of serpentine 1 km northeast of Fir Cap marks it at the southern border of the Mount Fillmore quadrangle. Farther north, highly contorted thin-bedded quartzite (a part of the downdragged lens) is exposed on both sides of the west branch of Downie River and the blastoclastic quartzite and schist of the Shoo Fly Formation on the ridge south of Bunker Hill.

In the Mount Fillmore quadrangle, long segments of the Melones fault zone are covered by Tertiary pyroclastic rocks. Two branches with intervening

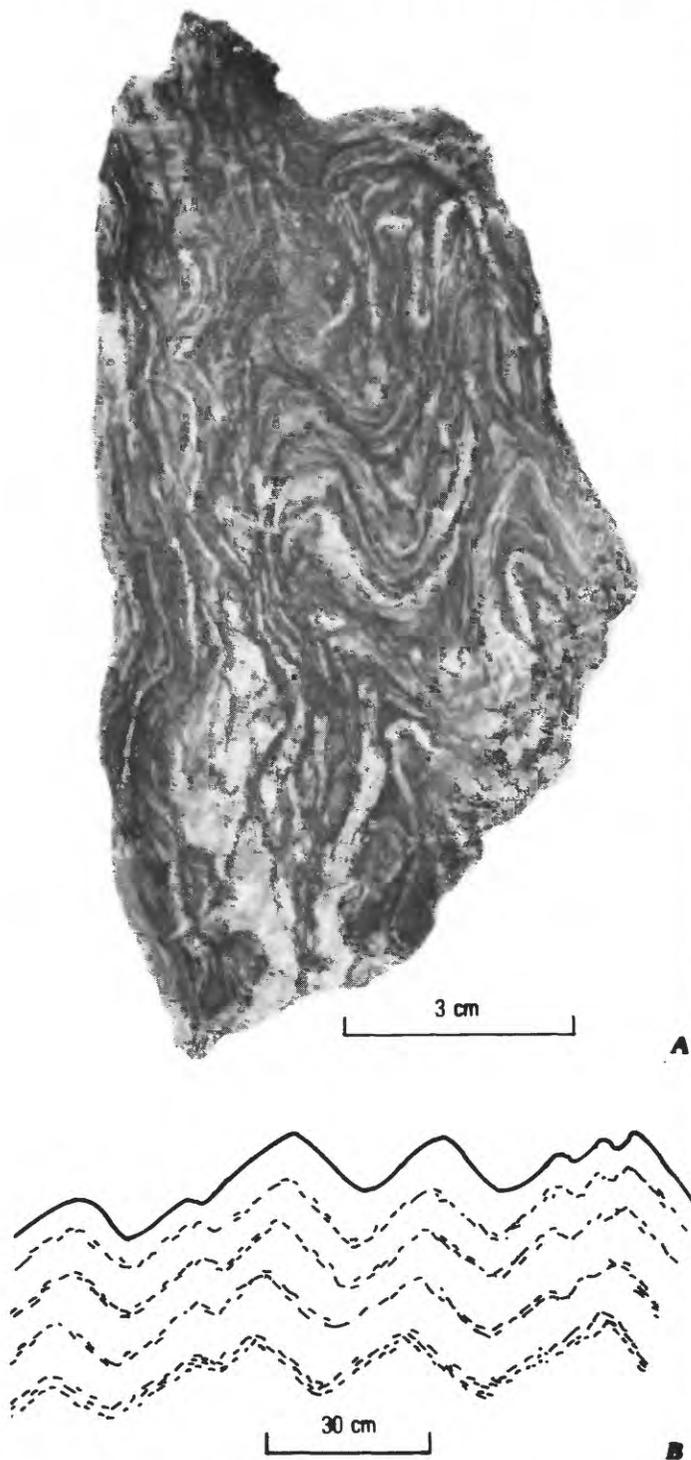


FIGURE 2.—Intense folding in quartz-rich rocks within Melones fault zone. A, Folds west of Downieville (loc. 2304); resemble flow folding of migmatites. Specimen from south-facing road cut. B, Chevron folds in quartzite east of Saddleback Mountain. South-facing wall.

serpentine are exposed in the deep gorge of Canyon Creek at Poker Flat; farther north, both branches are covered by Tertiary andesite for the distance of 5 km.

In the Bucks Lake quadrangle, the Melones fault zone separates the continentally derived orthoquartzite and schist of the Shoo Fly Formation on the east from the oceanic metachert and phyllite of the Calaveras Formation on the west. In the Onion Valley and La Porte quadrangles, slices of orthoquartzite and schist similar to rocks in the Shoo Fly occur within the serpentine belt between branching faults and in the center of the amphibolite dome west of the faults. These relations suggest that the major break along the Melones fault zone in this vicinity is not along the eastern contact of the Feather River ultramafic body as shown on the Chico Sheet (Burnett and Jennings, 1962) but rather between the slice of Shoo Fly-type rocks and the border zone of the amphibolite, where fault breccia is exposed along the South Fork of the Feather River. Southward this contact continues as a fault accompanied by a narrow body of serpentine. In the northeastern part of the La Porte quadrangle, Shoo Fly-type rocks are exposed on either side of the fault; rocks on the west are enclosed in the center of the circular amphibolite mass. North of the amphibolite and its border zone, in the west-central part of the Onion Valley quadrangle, the major break is along the eastern contact of the Feather River ultramafic body. Near the Middle Fork of the Feather River, the Shoo Fly-type rocks wedge out and the eastern contact joins the Melones fault proper.

Another major fault in the study area is continuous with the Dogwood Peak fault in the Bucks Lake quadrangle. In the La Porte quadrangle, this fault separates metasedimentary rocks of the Calaveras Formation from the metavolcanic rocks of the Franklin Canyon Formation. Discordance of structures on either side of it is evident, but no ultramafic rocks accompany it; this suggests that the fault may not extend downward as far as the other major faults in the Feather River area (the Melones, Camel Peak, and Big Bend faults; Hietanen, 1973a, 1976, 1977). In the southern part of the La Porte quadrangle and the northernmost part of the Goodyears Bar quadrangle, a fault parallel to the Dogwood Peak fault occurs 200 m east within the Calaveras Formation. This fault is marked by a breccia zone, 20 to 30 m wide, and two small lenses of serpentine and talc schist. It joins the major branch of the Dogwood Peak fault on Canyon Creek north of Head Dam.

In the central part of the Goodyears Bar quadrangle, south of the Tertiary pyroclastic cover on Bald Top, the major structural break is along the

Ramshorn fault, which separates Triassic rocks on the west from the Calaveras Formation on the east. It is accompanied by a very strongly sheared dark-green serpentine that extends from the Ramshorn Camp Ground on the North Yuba River northward along Ramshorn Creek, turns to the northwest and dives under the Tertiary pyroclastic rocks about 1 km southeast of Bald Top. The trends in the northwestern outcrops suggest that the Ramshorn fault continues under the pyroclastic andesite northward, joining the Dogwood Peak fault north of Bald Top. It is considered to be a southeastern branch of the Dogwood Peak fault. The Ramshorn fault is flanked on either side by lenses of metavolcanic rocks. The western lens is separated by a fault from Triassic metasedimentary rocks which consist of fine-grained black to white metachert and black phyllite, less thoroughly recrystallized and less deformed than rocks of the Calaveras Formation east of the Ramshorn fault. Well-preserved radiolarians in metachert just west of the fault yield a Middle and Late Triassic age (see "Mesozoic Metasedimentary Rocks").

At many places, where exposed on Fiddle Creek on the western border of sec. 26, T. 20 N., R. 9 E., the ultramafic body along the Ramshorn fault consists of soapstone and magnesite, but the northwest end of the body in section 26 is strongly sheared dark-green serpentine similar to that near the campground.

METASEDIMENTARY AND METAVOLCANIC SEQUENCES CALAVERAS FORMATION

The Calaveras Formation in the study area is continuous with the phyllite and metachert shown as the Calaveras Formation on the geologic map of the Bucks lake quadrangle (Hietanen, 1973a) to the northwest. In the southwestern part of the Onion Valley quadrangle, the major rock type is interbedded metachert and phyllite. A layer of light-gray fine-to medium-grained limestone, about 50 to 100 m thick, is interbedded with the metachert about in the middle of the exposed area. It extends more than 5 km as a straight band parallel to the north-northwest trends. Conodonts obtained from a section in the middle part of this layer (loc. 2619) yield an age which is not older than Pennsylvanian and not younger than Permian as determined by Anita Harris, U.S. Geological Survey. Bedding is vertical or dips steeply to the east. The straight line exposure pattern of this layer, clearly visible on aerial photographs, is typical of the flanks of steep isoclinal folds in the study area. The northern end of this limestone

layer is exposed on the west side of the lower drainage of Last Chance Creek between the 3,900- and 4,200-ft altitudes. Calcareous schist and dike rocks occupy its northward structural continuation along Sawmill Tom Creek. The southern end of the limestone is covered by Tertiary volcanic rocks. Study under the microscope indicates that this limestone consists of calcite with $\omega=1.668$ to 1.673, accompanied by very little magnetite, hematite, and sphene as accessory constituents.

South of the Tertiary volcanic rocks in the La Porte quadrangle, the western part of the Calaveras Formation consists mainly of phyllite with some metachert, the eastern part mainly of metachert with less phyllite. Because of the thinness and discontinuity of included metachert layers in the western part and of phyllite layers in the eastern part, these two rock types are not mapped separately. A few discontinuous layers of micaceous limestone and marble are interbedded with phyllite. The phyllite-rich western part continues southward into the Goodyears Bar quadrangle, where it is exposed between the Goodyears Creek and Ramshorn faults. A layer of calcareous black phyllite is interbedded with laminated phyllite just west of Goodyears Bar.

Most of the phyllite in the middle part of the Calaveras Formation is laminated and distinctly bedded: Interbedded in an irregular manner are micaceous layers, 1 to 20 cm thick, rich in muscovite, biotite, muscovite and chlorite, or chlorite, and layers rich in quartz. The color varies with the mineralogy from silvery white to greenish gray or brownish gray and to black with abundance of disseminated magnetite and carbonaceous material. Some layers exposed in roadcuts along Little Canyon Creek in the southern part of the La Porte quadrangle are exceptionally rich in carbonate, some of it in aggregates or in grains larger than the grains of other minerals. In the laminated phyllite, micaceous minerals separate 1-to 2-mm-thick layers consisting of quartz or quartz and altered feldspar. Pebbly layers are interbedded at many localities along Canyon Creek and Little Canyon Creek. In some of these layers, pebbles are small (1 to 5 mm long); in others, they may range from 1 to 2 cm in length. Most pebbles consist of metachert or quartzite, but calcite or calcite-quartz pebbles are common.

Metachert in the Calaveras is similar to the metachert described from the Bucks Lake quadrangle (Hietanen, 1973a). Most of it is thoroughly recrystallized and strongly deformed, impairing the preservation of radiolarians. It is thin bedded, consisting of 2-to 5-cm-thick light-gray to white fine-grained to granular quartz-rich layers separated by thin (2-to

10-mm-thick) mica-rich layers. Interbedded with the metachert are phyllite layers that commonly range in thickness from one to several meters and separate units of metachert that range from 5 to 50 m. Micaceous minerals in the metachert are muscovite and chlorite; magnetite is the common accessory mineral.

On Canyon Creek 1 km west of Poker Flat (loc. 2392), a layer of blastoclastic quartzite, about 10 m thick, is interbedded with metachert and phyllite. This layer continues south-southwest to the end of the ridge north of Deadwood Creek (loc. 2406). Farther in the southwest, just north of the Tertiary pyroclastic andesite on Deadwood Peak, similar quartzite and metachert are exposed between two serpentine lenses (loc. 2407). In all these localities, quartzite is distinctly bedded and resembles the blastoclastic quartzite of the Shoo Fly Formation in the Bucks Lake quadrangle; it was deposited as a quartz sand that could have been carried out to the sea from the continental shelf during its temporary uplift.

A layer of white to gray marble, about 10 m thick, is exposed along an old logging road on the north side of Canyon Creek in the south-central part of the La Porte quadrangle (loc. 2149). This marble layer is bordered by muscovite phyllite on the west and by quartzite on the east. The eastern half of the outcrop consists of thick beds of white marble, whereas the western half is thin bedded, light gray, and grades through micaceous limestone to phyllite with straight well-defined bedding planes. The gray beds break into long slabs parallel to well-developed lineation. Another layer of medium-grained light-gray marble along Canyon Creek, about 4 m thick, is interbedded with metachert 0.5 km north of the mouth of Morristown Ravine.

Micaceous gray marble is interbedded with phyllite in places along Little Canyon Creek (locs. 2229, 2232). At locality 2229, lenses of white marble (2 to 10 mm thick and 3 to 10 cm long) are embedded in gray micaceous carbonate rock that contains epidote, quartz, magnetite, and subhedral red pseudomorphs of chlorite + hematite after garnets and is dusted by carbonaceous material. A carbonate-rich layer at locality 2232 contains tiny needles of tremolite, green chlorite, epidote clouded by leucoxene, and some quartz.

The attitudes of bedding planes suggest that the Calaveras Formation is isoclinally folded on a south-southeast-plunging axis. Small folds on this axis can be observed in good outcrops (fig. 3A). A second folding and wrinkling on eastward- or southwestward-plunging lineation occurs locally. The foliation transects the bedding at and near the crests of the folds (fig. 3B) but parallels it along the flanks. In

many places, shearing parallel to the foliation has broken the beds into lenses (fig. 3C). Parallelism of the mica flakes with the axial planes of the folds shows that recrystallization to the epidote-amphibolite facies took place during the major period of deformation.

METAVOLCANIC ROCKS WITHIN THE CALAVERAS FORMATION

Two large and several small elongate bodies of metavolcanic rocks are within the Calaveras Formation. Some of these occupy synclinal areas or are next to faults, but many thin discontinuous layers are interbedded with rocks of the Calaveras Formation. The largest body, well exposed along Canyon Creek south of the mouth of Morristown Ravine and along logging roads to the southeast, occupies a synclinal area and seems less thoroughly recrystallized and less deformed than the other metavolcanic rocks in this area. The rocks in this body are interbedded basaltic meta-andesite, agglomerate, and metatuff. The basaltic meta-andesite is a slightly foliated greenish-gray rock containing small green phenocrysts of augite and scattered black phenocrysts of hornblende. Agglomeratic layers consist of light-colored andesitic fragments, 5 to 15 cm long, embedded in a darker matrix. In the tuffaceous layers, fragments range in length from very small to 1 cm.

A well-exposed section through these rocks is in the steep cliffs along Canyon Creek south of the mouth of Morristown Ravine. In the northern and southern part of this section, layers are vertical. In the central part, flat-lying layers of agglomerate and

basaltic meta-andesite are exposed in the bottom of the creek. In the agglomerate layers, subangular to elongate fragments of light-greenish-gray meta-andesite are embedded in a dark foliated matrix (fig. 4). The structures and contrasting colors are striking on clean underwater outcrops. Most fragments in the agglomerate layers have their long dimension subparallel to the bedding or to the transecting cleavage.

Thin sections show that the basaltic meta-andesite that appears massive in outcrops is made up of tiny fragments of altered volcanic rock consisting of epidote, chlorite, amphibole, albite, and leucoxene and of subhedral to euhedral crystals of augite, hornblende, and altered plagioclase. Some fragments have altered plagioclase laths embedded in a fine-grained mixture of chlorite, actinolitic hornblende, and sericite. All plagioclase is altered to muscovite or sericite and a fine-grained mesh of zoisite. The crystals of augite and olive-brown hornblende are well preserved.

Lapilli tuff with small fragments of metabasalt, meta-andesite, and metadacite is interbedded with basaltic meta-andesite at higher altitudes on the southeast side of Canyon Creek. Thin sections show two types of metabasalt among the fragments, a porphyritic and a fine-grained variety. In the porphyritic metabasalt, phenocrysts of green hornblende and altered plagioclase are embedded in a fine-grained groundmass consisting of albite, sericite, chlorite, epidote, and leucoxene. In the fine-grained metabasalt, slender laths of altered plagioclase and a few pseudomorphs consisting of chlorite are in the groundmass of albite, epidote, chlorite, and leucoxene. Meta-andesite fragments are rich in

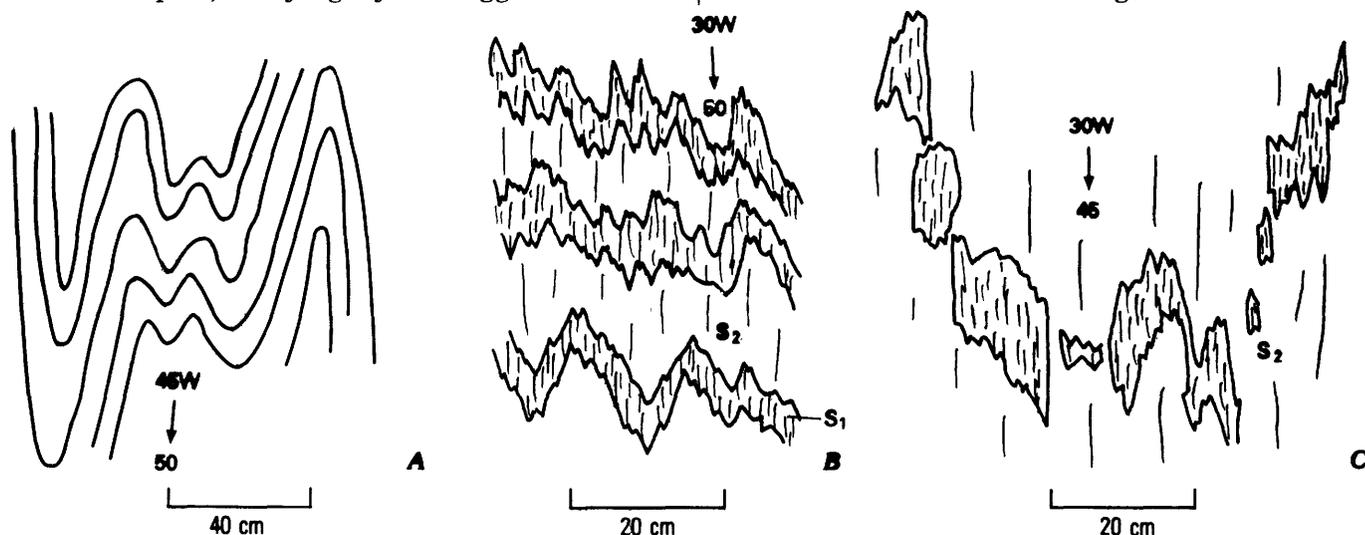


FIGURE 3.—Folding and cleavage in the Calaveras Formation along Canyon Creek. A, Folds on a south-southeast-plunging axis in metachert 200 m north of the mouth of Happy Hol Ravine. B, Transecting cleavage (s_2) in light-brown phyllite with dark-brown to black layers (s_1) 250 m north of Morristown Ravine. C, Dark-brown bed in folded phyllite, lensed by shearing parallel to foliation (s_2). Same location as B.

epidote and contain less amphibole than the basaltic fragments. Altered phenocrysts of plagioclase and quartz characterize the dacitic fragments. Some tiny angular fragments consisting of small grains of epidote and chlorite are outlined by hematite-colored dark material. The groundmass in which all these fragments are enclosed consists of chlorite, sericite, albite, epidote, hematite, and magnetite.

A layer of purplish-gray metabasalt and meta-andesite with pillow structures is well exposed on the tributaries of Reese Ravine at the border between the La Porte and Mount Fillmore quadrangles. These metavolcanic rocks extend from Reese Ravine southward to the vicinity of Old Mill Creek, where pillow structures are exceptionally well exposed in roadcuts. The layer is 350 m wide and is bordered on either side by metachert of the Calaveras Formation. The northern and southern end is covered by Tertiary pyroclastic rocks. Boulders of metabasalt containing slightly elongate bombs, 5 to 10 cm long, occur along its eastern margin on Reese Ravine.

The pillow basalt and the fine-grained layers next to it seem foliated on the outcrops, but thin sections show that the planar structure is most likely a primary flow structure. The groundmass in the pillows and the bombs consists of radiating bundles of long thin plagioclase laths, many of them curved and altered to muscovite and epidote. Leucoxene, dendritic ilmenite, magnetite, and hematite are inter-

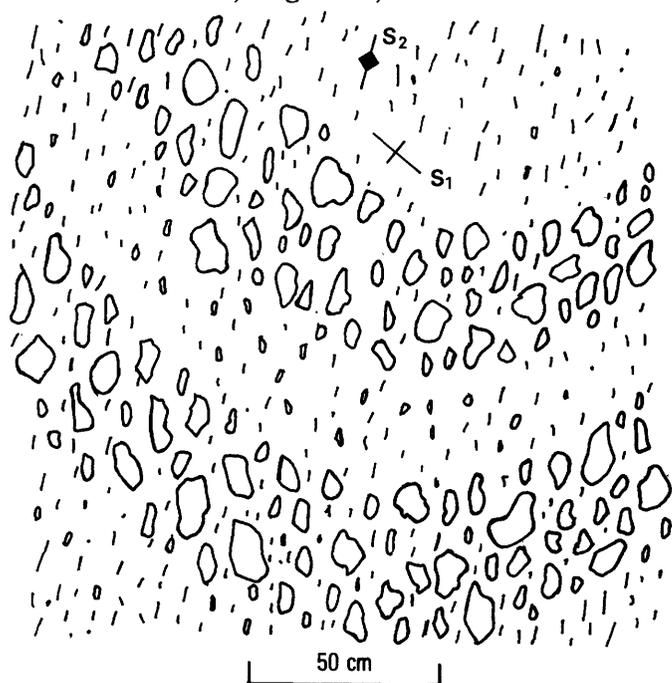


FIGURE 4.—Agglomerate layers in folded basaltic meta-andesite on Canyon Creek south of mouth of Morristown Ravine. Light-colored fragments of meta-andesite in matrix colored dark by iron oxides. Bedding (s_1) and foliation (s_2) are vertical.

stitial. Small phenocrysts of plagioclase with straight crystal faces are scattered or form small clusters. The interstitial material between the bombs consists mainly of large crystals of epidote, some aggregates of chlorite, and radiating bundles of small magnetite grains.

The western border zone of the occurrence on the south side of Reese Ravine (loc. 2238) consists of thoroughly recrystallized hornblende-epidote-chlorite rock in which light-green hornblende prisms are in random arrangement and large well-crystallized light-yellow epidote grains and light-green chlorite are interstitial or form clusters partly clouded by leucoxene. Sphene and magnetite occur as accessory minerals.

A sample collected from the purplish-gray rock with pillow structures in the center of the occurrence on the south side of Reese Ravine (loc. 2237) was analyzed chemically. The result (table 1, anal. 2237) shows an exceptionally high content of ferric iron and potassium, whereas the percentages of silicon, magnesium, total iron, calcium, and sodium are typical of meta-andesites. The higher rate of oxidation of iron in comparison with the other andesitic rocks could be in part a primary feature due to conditions of extrusion and in part a result of later metamorphic processes and weathering of magnetite to hematite.

On the North Yuba River, metadacite and meta-andesite including some metatuff are exposed on the east side of the Ramshorn fault. The metadacite is light greenish gray and contains phenocrysts and amygdules of quartz. Actinolite, chlorite, albite, and epidote, all clouded by leucoxene, are the major constituents. Thin sections of meta-andesite show a relict fragmentary texture. Most of the rock is a well-foliated medium-grained mixture of actinolite, chlorite, and albite and some large grains of calcite and subhedral to rounded phenocrysts of albite and augite. Embedded in this rock (loc. 2534) are lenses (2 to 5 mm long) of porphyritic metadacite with plagioclase and augite phenocrysts in a fine-grained groundmass consisting of round to elongate grains of albite and quartz and an interstitial mixture of chlorite and zoisite. In the andesitic part of the rock, the pale-green to colorless actinolite is the major dark constituent. It occurs in slender prisms that show varying degrees of parallelism with the plane of foliation. Many albite and augite phenocrysts have their longest dimension parallel to the foliation, but some are clustered. The layers of metatuff are medium greenish gray and foliated and consist of quartz, albite, epidote, amphibole, and chlorite in varying proportions. Many layers are thin bedded;

Table 1.—*Chemical composition and trace elements of metagabbro, amphibolite, metavolcanic rocks, and andesite*—Continued

[Chemical analyses of 2371, 2592, and 2237 by Sarah T. Neil; 1589 by Edythe Engleman; X-ray fluorescence major-element determination for 2043, 2106, 2067, 2155, and 2101 by B. King. Chemical analyses for FeO, CO₂, H₂O by Sarah T. Neil and J. H. Tillman. Spectrographic analyses by M. L. Retzlaff and Chris Heropoulos]

Specimen.....	2371	2043	2106	2592	1589	2067	2155	2237	2101	
Rock type.....	Meta-gabbro	Amphibolite	Volcanic bomb in metatuff	Amphibolite	Basaltic meta-andesite	Meta-andesite	Meta-andesite	Meta-andesite	Platy andesite	
Locality.....	1 km southwest of Fir Cap	Slate Creek Northeast of Yankee Hill	Slate Creek 300 m east of French Camp	1 km north of Claremont	Simon Ravine	1 km south- southwest of La Porte	2 km south- southwest of La Porte	Reese Ravine	East of Goat Mountain	
Epinorm, in molecular percent										
Quartz.....	(-6.13)	(-1.12)	---	---	3.23	.67	4.58	8.60	10.06	22.00
Orthoclase.....	1.10	1.19	.43	.43	1.48	11.10	4.50	7.38	5.82	3.84
Albite.....	27.89	30.36	26.79	26.79	28.11	11.43	31.24	23.18	38.56	33.47
Muscovite.....	---	---	---	---	---	---	---	---	18.84	7.42
Zoisite.....	28.58	20.91	26.89	26.89	24.76	34.73	29.67	29.43	11.51	22.21
Actinolite.....	28.43	30.29	35.04	35.04	33.69	24.89	13.96	13.90	---	---
Antigorite.....	16.80	8.90	---	---	---	11.67	10.19	11.48	4.49	7.65
Magnetite.....	1.15	4.29	4.65	4.65	5.10	3.57	4.11	3.80	---	2.43
Hematite.....	---	---	---	---	---	---	---	---	6.72	---
Ilmenite.....	1.87	4.58	1.68	1.68	2.80	1.08	1.47	1.49	2.69	.58
Rutile.....	---	---	---	---	---	---	---	---	.20	---
Apatite.....	.16	.54	.22	.22	.40	.88	.27	.60	.94	.36
Calcite.....	.19	.06	4.90	4.90	.39	.03	.06	.19	.22	.08
Total.....	100.00	100.00	100.60	100.60	99.96	100.00	100.00	100.00	100.00	100.00
Trace elements, in parts per million										
B.....	14	---	---	---	---	---	---	---	110	---
Ba.....	190	72	42	42	150	590	260	500	450	850
Be.....	---	---	---	---	---	---	---	---	4	---
Co.....	100	90	47	47	30	52	28	56	29	11
Cr.....	220	170	630	630	100	210	29	39	240	69
Cu.....	310	29	10	10	20	160	97	260	120	29
Ni.....	140	62	100	100	50	40	23	26	82	23
Sc.....	77	73	66	66	20	60	55	54	44	30
Sr.....	180	140	200	200	150	600	260	360	490	700
V.....	600	160	140	140	200	440	140	150	250	96
Y.....	44	170	64	64	50	31	44	64	56	24
Zn.....	220	400	240	240	150	---	250	290	200	190
Zr.....	26	200	140	140	100	130	110	140	230	250
Ga.....	34	32	23	23	20	21	22	24	39	24
Yb.....	9	17	7	7	7	3	6	8	9	2

augite phenocrysts have been preserved in a few layers, as, for example, in those south of Eureka Diggings. Thin sections show that these phenocrysts are strongly deformed and altered to actinolite and chlorite along the cracks and borders. The groundmass is fine grained and foliated and consists of albite, epidote, tremolite, and chlorite, all clouded by leucoxene. Subhedral medium-size grains of pyrite and small grains of magnetite occur as accessory minerals. Sphene has been altered to leucoxene.

A foliated metabasalt consisting of prisms of green amphibole, albitic plagioclase, epidote, sphene, magnetite, and some sericite is exposed for 0.5 km along Onion Valley Creek in the southwestern part of the Onion Valley quadrangle. Cracks in this rock are filled with albite and chlorite; amgdules are epidote. On its west side, the metabasalt is bordered by a layer of metatuff. Another lens of metabasalt, 250 m downstream, consists of very small prisms of tremolitic amphibole, epidote, albite, and leucoxene. Fragmental texture is recognizable, even where the rock is strongly deformed. Cracks are filled with albite, quartz, epidote, chlorite, and tremolite.

Augite-bearing metabasalt forms steep outcrops

along Canyon Creek about 1 km west of Poker Flat. This metabasalt is brecciated and contains inclusions of metachert. Augite and plagioclase occur as phenocrysts in a groundmass consisting of green chlorite, epidote, albite, leucoxene, and magnetite. Plagioclase phenocrysts are altered to a mixture of zoisite, albite, and some muscovite; cracks are filled with albite. The western part of this small stocklike mass consists of fragmental metarhyolite with inclusions of metachert and veinlets and amygdules of quartz and calcite. Quartz and albitic plagioclase occur as phenocrysts. The groundmass consists of quartz, albite and some biotite, hornblende, and chlorite and is heavily dusted with magnetite.

METAMORPHIC ROCKS WITHIN THE MELONES FAULT ZONE

Most of the metasedimentary rocks within the Melones fault zone resemble rocks of either the Shoo Fly Formation or the Calaveras Formation except that they are strongly deformed and more highly recrystallized. In the northern part of the area, a 12-km-long slice of Shoo Fly quartzite and schist is within the fault zone; in the southern part, the enclosed metamorphic rocks are lithologically sim-

ilar to the Calaveras Formation. Discontinuous layers and lenses of brecciated metavolcanic rocks embedded in contorted metasedimentary quartz-rich rocks between Goodyears Creek and the Melones fault contain crossite, pumpellyite, and lawsonite, typical low-temperature—medium-pressure minerals commonly found along subduction zones.

The southernmost occurrence of metasedimentary rocks within the Melones fault zone in this area occupies a wedge-shaped area between the serpentine along the Goodyears Creek fault and the Melones fault proper, extending 13 km north from the North Yuba River. It is partly covered by Tertiary volcanic rocks near Fir Cap, Saddleback Mountain, and Democrat Peak. The northernmost exposure is a small window in the pyroclastic rocks west of Cloud Splitter, 13 km north of Downieville. These metasedimentary rocks are similar in composition to the interbedded metachert and phyllite of the Calaveras Formation but were recrystallized to fairly coarse grained rocks, intricately folded and contorted. There is a notable difference in structures and style of folding between the northern and southern parts of these metasedimentary rocks. In the north, particularly in the eastern part of the occurrence, the layers of thin-bedded metachert, recrystallized to white granular quartzite with micaceous layers, show intense small-scale chevron folding (fig. 2B) with amplitudes of 3 to 10 cm and wavelengths of 5 to 30 cm. Two sets of lineation are common: the axis of the small folds and a lineation (fine wrinkling) at an angle to it. In the southern part, flow folding, similar to that in migmatites and trench melanges, is common (fig. 2A), and lineation is parallel to the fold axes. This difference in the style of folding indicates a difference in plasticity of the material folded and hence in the pressure-temperature conditions during deformation. The southern part of this large lens-shaped slice of metamorphic rocks was dragged farther down during the subduction than the northern part, which remained competent.

In the southern part of the lens, the chert layers have recrystallized as laminated micaceous quartzite in which quartz-rich layers are 4 to 5 mm thick and the micaceous laminae are about 1 mm thick. Thin sections show that the quartz grains have sutured borders and range in size from tiny to 1 mm, rarely more. Muscovite and chlorite form irregular laminae. Sphene, partly altered to leucoxene, and magnetite occur as accessory minerals. The shaly layers have recrystallized as muscovite-chlorite schist in which quartz is segregated into 1- to 3-mm-thick laminae. The white mica (loc. 2304) with a small optic angle is probably phengite. Small wisps of stilpnomelane

occur in some layers east of Rosassco Ravine. Scattered aggregates of sphene partly altered to leucoxene and grains of magnetite and ilmenite occur as accessory minerals.

The crossite-bearing metavolcanic rocks are well exposed in roadcuts along the North Yuba River 1 to 2 km east of Goodyears Bar, near Rosassco Ravine, and just west of Downieville. The lens-shaped bodies, a few meters to 1 km in length, consist of brecciated metabasalt and basaltic meta-andesite and metatuff. Typical melange is seen at a few localities, as just east of Rosassco Ravine, where small blocks (1 to 5 m long) of metabasalt are included in a micaceous matrix. Similar volcanic breccia and metatuff are exposed on a ridge north of Grizzly Peak (loc. 2572) and on road cuts along the road from Downieville to Saddleback Mountain.

The outcrops on either side of Rosassco Ravine about 2 km west of Downieville are typical of the crossite-bearing metavolcanic rocks: greenish-gray basaltic breccia in which individual fragments, 1 to 20 cm or even several meters long, are embedded in bluish-green sheared matrix that consists of crossite, actinolitic hornblende, chlorite, epidote, and albite, or, more rarely, of chlorite, actinolite, albite, and quartz, or of albite, epidote, and calcite. In most outcrops, fragments consist of fine-grained actinolite-chlorite-epidote-albite rock with scattered groups of tiny grains of sphene and magnetite or ilmenite. In some fragments, porphyritic texture has been preserved. Lath-shaped phenocrysts of plagioclase have recrystallized as a mosaic of small grains of albite and epidote, and phenocrysts of augite were pseudomorphosed to chlorite that includes epidote and some stilpnomelane. Blue crossite is mainly between the fragments, more rarely pods or radiating prisms within the fragments. Chlorite is pale green with low interference colors. Epidote is in subhedral to anhedral pale-yellow crystals embedded in chlorite and amphiboles. Sphene is in elongate clusters of small grains partly altered to leucoxene. Magnetite and iron sulfides (pyrite and pyrrhotite) occur as accessory minerals. Lawsonite is the main constituent in brecciated meta-andesite west of Downieville (loc. 2523). Pumpellyite, in elongate grains and aggregates, is embedded in metabasalt rich in light-blue amphibole 2 km east of Goodyears Bar (loc. 2546). Brown stilpnomelane in radiating aggregates and wisps is scattered or embedded in leucoxene and chlorite. Calcium carbonate, quartz, and albite fill some of the cracks. Clusters of round grains of apatite occur east of Rosassco Ravine.

The lawsonite-rich rock west of Downieville is bluish-green-gray breccia in which lawsonite is the

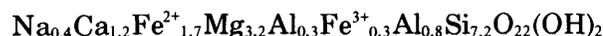
main constituent of fragments and also occurs in coarser grained matrix with chlorite, white mica (phengite?), quartz, and stilpnomelane. In the fragments, the slender elongate plates of lawsonite with bright interference colors and straight extinction form small slightly radiating aggregates. The other constituents, chlorite, phengite, hematite, and leucocoxene, are interstitial.

Pumpellyite-bearing rock east of Goodyears Bar (loc. 2546) is greenish blue, medium grained, and consists of light-blue amphibole, colorless pumpellyite, pale-green chlorite, sphene, leucocoxene, and some ilmenite. The pumpellyite occurs in colorless elongate grains (0.1 to 0.2 mm long) among blue amphibole prisms or forms round to elongate aggregates with interstitial chlorite. It shows indices of refraction $\alpha = 1.676(1)$, $\beta = 1.682(1)$, $\gamma = 1.690(1)$, and $\gamma \Delta c \sim 21^\circ$.

The amphibole in specimen 2546 has indices of refraction

α (colorless) = 1.637(2), β (pale blue green) = 1.651(2), and γ (light blue) = 1.660(2) and $2V \sim 70^\circ$.

The composition of this amphibole was obtained from an X-ray fluorescence analysis of a mineral concentrate that contained 20 percent pumpellyite (analyst, Bi-Shia King, U.S. Geological Survey). After deduction of the pumpellyite, the remaining oxides yielded a composition of amphibole. Its calculated formula.



indicates that it is chemically similar to the green amphiboles in meta-andesite and metadacite in the Bucks Lake quadrangle (Hietanen, 1974). According to the nomenclature by Leake (1978) it is magnesiohornblende.

Most of the amphibole in fragments of brecciated metabasalt near Rosassco Ravine is light-bluish-green to pale-green actinolitic hornblende with indices of refraction

$\alpha = 1.623$, $\beta = 1.627(1)$, $\gamma = 1.635(1)$ and $\gamma \Delta c = 14^\circ$

as measured in specimen 2550. Twenty meters east in specimen 2549, light-blue hornblende has higher indices of refraction,

$\alpha = 1.638(2)$, $\beta = 1.652(2)$, $\gamma = 1.660(2)$,

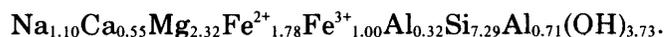
closely similar to indices for the light-blue actinolitic hornblende in specimen 2546.

The blue amphibole between fragments is fibrous and shows blue pleochroism parallel to the length of

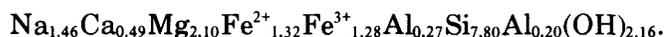
the fibers and mixture of violet and lavender across it. The indices of refraction measured in specimen 2647 are

$\alpha = 1.656(1)$, $\beta = 1.666(1)$, $\gamma = 1.670(1)$ and $\gamma \Delta c = 3^\circ$.

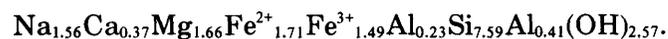
Chemical analysis by Sarah Neil, U.S. Geological Survey, shows 3.8 percent sodium and a high percentage of water (table 2, anal. 2647h). Calculation of the analysis on the basis of 23(O) yields the generalized formula



A blue amphibole just east of Rosassco Ravine has indices of refraction $\alpha = 1.658(2)$, $\beta = 1.670(2)$, and $\gamma = 1.672(2)$ and a high sodium content (table 2, anal. 2554h). Calculation of the chemical analysis on the basis of 23(O) yields the formula



An optically similar blue amphibole from the west side of Rosassco Ravine was analyzed by Bi-Shia King, U.S. Geological Survey, by the X-ray fluorescence method. The result (table 2, anal. 2306h) shows a high percentage of ferric and ferrous iron and sodium and low percentage of aluminum and calcium. Calculation of the basis of 23(O) yields the generalized formula



The high sodium content and high $\frac{\text{Fe}^{3+}}{\text{Fe}^{3+} + \text{Al}^{\text{VI}}}$ ratio (0.87) would indicate composition of riebeckite by Leake's classification (1978), but the optical properties are those reported for crossites (Winchell and Winchell, 1951; Deer and others 1963; Borg, 1967) and the Y vibration direction is parallel to the length of the fibers, as typical of crossite.

Optical properties determined with the super-spindle stage on goniometrically oriented single crystal of this crossite (anal. 2306h) by R.C. Erd, U.S. Geological Survey, are α (pale yellow) = 1.659(2), β (blue) = 1.670(2), γ (purple) = 1.675(2), $\beta \Delta c = 0-2^\circ$, $\gamma \parallel b$ and $2V \alpha = 60^\circ(3)$ measured; calculated $2V = 68^\circ$.

The crossite between the fragments in basaltic breccia 250 m west of Coyote Ravine (loc. 2303) has somewhat lower indices of refraction,

$\alpha = 1.649(1)$ and $\gamma = 1.654(1)$,

indicating about 50 percent riebeckite according to Winchell's diagram (1951). The fragments, 3 to 30 cm long, consist of pale-green actinolite, chlorite, epidote, sphene, and some quartz, calcite, muscovite, and

TABLE 2.—*Chemical analyses and calculated formulas of amphiboles and pyroxene*

[Analyses on crossite in metabasalt (2306, 2554, and 2647), blue-green hornblende in metagabbro (2637) and amphibolite (2043), and brown hornblende (2371h) and diopside (2371d) in metagabbro. Analysts: Chemical analyses of 2554h, 2647h, 2637h, 2043h, 2371h, and 2371d by Sarah T. Neil. X-ray fluorescence analyses of 2306h by B. King; FeO, Na₂O, and H₂O of 2306h by P. Klock. Trace elements: T. Fries (2554h, 2647h, 2637h), Chris Heropoulos (2043h), M. L. Retzlaff (2371h, 2371d), and R. Lerner (2306h)]

	2306h	2554h	2647h	2637h	2043h	2371h	2371d
Weight percent							
SiO ₂	50.62	54.4	49.2	46.5	42.76	42.98	50.02
Al ₂ O ₃	3.64	2.8	5.9	10.4	12.32	12.32	3.50
Fe ₂ O ₃	13.19	11.85	8.96	5.28	4.48	1.13	.97
TiO ₂.....	.04	.48	.57	.62	.53	2.27	.43
FeO.....	13.58	10.73	14.08	10.94	15.66	15.31	11.20
MgO.....	7.41	9.84	10.52	11.48	8.60	10.09	11.85
MnO.....	.14	.22	.28	.33	.27	.21	.30
CaO.....	2.31	3.20	3.49	11.31	10.55	10.98	20.54
Na ₂ O.....	5.37	5.22	3.80	1.36	2.26	2.30	.48
K ₂ O.....	.18	.07	.07	.25	.29	.14	.01
P ₂ O ₅.....	.13	.12	.14	.14	.00	.03	.03
H ₂ O ⁺	2.56	2.26	3.78	2.02	2.37	1.77	.68
H ₂ O ⁻10	---	---	---	.02	.01	.02
CO ₂	---	---	---	---	.00	(.12)	(.15)
Cl.....	---	---	---	---	.05	---	---
F.....	---	---	---	---	.02	---	---
Total.....	99.27	101.19	100.79	100.63	100.13	100.10	100.17
-O=F.....	---	---	---	---	0.01	---	---
Total.....	---	---	---	---	100.12	---	---
Trace elements, in parts per million							
Be.....	3	---	---	1	---	---	---
B.....	18	---	---	15	4	---	---
Ba.....	21	---	---	34	14	2	2
Co.....	56	---	---	45	49	30	20
Cr.....	11	---	---	22	88	70	50
Cu.....	18	---	---	55	13	30	100
Ni.....	75	---	---	22	42	50	20
Sc.....	16	---	---	110	79	20	30
Sn.....	18	---	---	---	---	---	---
Sr.....	---	---	---	11	16	5	2
V.....	420	---	---	570	660	200	150
Y.....	11	---	---	53	35	20	15
Zn.....	150	---	---	---	130	200	150
Zr.....	130	---	---	100	240	---	---
Ga.....	16	---	---	27	29	20	20
Yb.....	---	---	---	3	11	5	2
La.....	---	---	---	20	---	---	---
Structural formula							
Si.....	7.59	7.80	7.29	6.74	6.43	6.36	1.90
Al.....	.41	.20	.71	1.26	1.57	1.64	.10
Al.....	.23	.27	.32	.51	.61	.59	.06
Fe ³⁺	1.49	1.28	1.00	.58	.51	.13	.03
Ti.....	0	.05	.06	.07	.06	.25	.01
Fe ²⁺	1.60	1.28	1.28	1.33	1.89	1.80	.36
Mg.....	1.66	2.10	2.32	2.48	1.93	2.23	.67
P.....	.02	.02	.02	.02	---	.00	---
Fe ²⁺10	.01	.46	---	.08	.10	---
Mn.....	---	---	---	.01	---	---	---
Mn.....	.01	.03	.04	.03	.03	.03	.01
Ca.....	.37	.49	.55	1.76	1.70	1.74	.84
Na.....	1.52	1.45	.95	.21	.19	.13	.04
Na.....	.04	---	.14	.17	.47	.53	---
K.....	.03	.01	.01	.05	.06	.03	---
OH.....	2.57	2.16	3.73	1.95	2.38	1.75	.17
Cl.....	---	---	---	---	2.40	---	---
F.....	---	---	---	---	.01	---	---
Mg.....	.49	.62	.57	.65	.49	.54	.65
Mg+Fe ²⁺	---	---	---	---	---	---	---
Fe ³⁺87	.83	.76	.53	.46	.18	---
Fe ³⁺ Al ¹	---	---	---	---	---	---	---
α.....	1.659(1)	1.658(2)	1.656(2)	1.658(2)	1.661(1)	1.663(1)	1.693(1)
β.....	1.670(1)	1.670(2)	1.666(2)	1.672(2)	1.674(1)	1.691(1)	1.701(1)
γ.....	1.675(1)	1.672(2)	1.670(2)	1.680(2)	1.683(1)	1.707(1)	1.717(1)

magnetite

Crossite with α (pale yellow to colorless) = 1.670(2), β (blue) = 1.676(2), γ (violet) = 1.677(2), reddish-brown stilpnomelane with γ = 1.664(2), and green epidote fill the cracks in a fine-grained metabasalt consisting of chlorite, epidote, albite, crossite, stilpnomelane, and leucoxene north of Grizzly Peak (loc. 2572). Interbedded tuffaceous layers are rich in blue amphibole and epidote.

In the southeastern Onion Valley quadrangle and northeastern La Porte quadrangle, the metasedimentary rocks within the Melones fault zone are blastoclastic quartzite and interbedded mica schist. The quartzite layers are coarse-grained bluish-gray rocks that contain muscovite, chlorite, and in places some garnets; they grade to muscovite-chlorite-(garnet) schist. Much of the quartzite is strongly deformed and laminated, but parts of most beds show blastoclastic texture similar to that typical of the quartzite of the Shoo Fly Formation in the Bucks Lake quadrangle (Hietanen, 1973a, p. 4-6). In these beds, round clear quartz grains are embedded in a fine-grained matrix of quartz and muscovite. In the strongly deformed beds, elongate quartz grains are in thin laminae separated by paper-thin long flakes of muscovite. Chlorite, garnet, amphibole, and zoisite are common in thick micaceous layers.

The schist interbedded with the quartzite is coarse grained, rich in muscovite, and contains some chlorite and scattered garnets. Thin layers and lenses consisting of bluish-gray quartz similar to that in the quartzite are common. Some layers contain individual large oval grains of bluish-gray quartz embedded in a mica-rich matrix; these beds are similar to parts of the Shoo Fly Formation in the Bucks Lake quadrangle.

Foliation is parallel to the bedding, and a strong lineation is along the dip (α lineation). Fold axes parallel to the lineation in the enclosing amphibolite suggest a contemporaneous deformation (fig. 5). The serpentine along the Melones fault cuts the quartzite beds at an angle.

In the northeastern part of the La Porte quadrangle, layers of similar orthoquartzite and interbedded mica schist are exposed in the center of the circular amphibolite mass that occupies about 80 km² in the east-central part of the area, probably an uplifted volcanic neck with a collapsed caldera or cauldron. In two localities south of the central orthoquartzite-schist exposure, similar quartzite occurs as long lens-shaped inclusions in the amphibolite. These quartzite layers, like those within the Melones fault zone, were deposited as quartz sand near a continental margin.

A unique feature of all these metasedimentary rocks is their coarse grain size and exceptionally strong deformation. In many layers, quartz grains are drawn into long lenses, the longest dimension of which is 4 to 15 times that of the shortest. In places, thin layers of quartzite in the schist have been boudinaged. Two sets of folds are common: The axes of large folds plunge eastward; the axes of small folds and wrinkling plunge 35° to 60° southward.

FRANKLIN CANYON FORMATION

The Franklin Canyon Formation in the southwestern part of the study area is continuous with the andesitic eastern part of this formation in the American House and Strawberry Valley quadrangles. The major rock type is a fine-grained greenish-gray slightly foliated meta-andesite that in places contains small phenocrysts of albite and hornblende. Well-preserved phenocrysts of augite occur locally in its eastern part. Tuffaceous layers with a distinct bedding and a strong foliation parallel to it are common. Small elongate masses of metabasalt and silicic differentiates, metadacite and metasodarhyolite, are interlayered with meta-andesite in many places.

Along the North Yuba River Triassic metasedimentary rocks overlie and may interfinger with the meta-andesite and metatuff of the Franklin Canyon Formation; these relations indicate that the volcanism in this southeastern part may have continued to Triassic time. Accordingly, the age of the Franklin Canyon Formation is now considered to be late

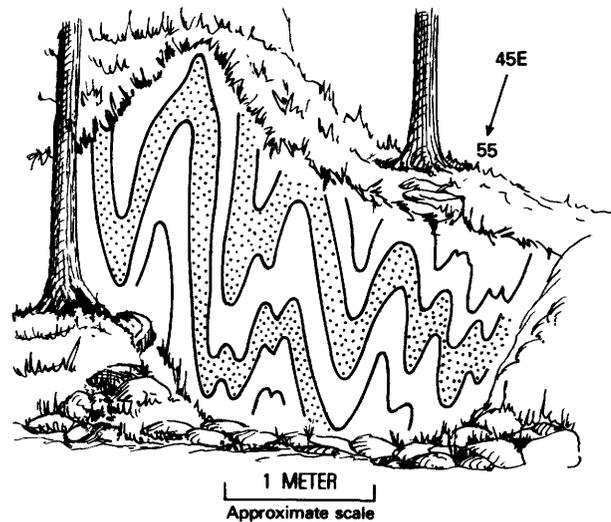


FIGURE 5.—Folding on a west-southwest-plunging axis in interbedded quartzite and muscovite-biotite schist of the Shoo Fly Formation. Vertical south-facing cut along an old flume at 1,600-m altitude on north side of Slate Creek 350 m southwest of mouth of Gibson Creek. Arrow indicates minor fold axis, showing plunge.

Paleozoic and Triassic (?). On the west, in the Strawberry Valley quadrangle (Hietanen 1976, pl. 1), this formation is bordered by serpentine and metabasalt, probably a remnant of an oceanic lithosphere, on which the island arc (the Franklin Canyon Formation) was built. This remnant of a dismembered ophiolite is well exposed along Slate Creek, 3 km west of Indian Valley, and to the north.

Thin sections show that most of the meta-andesite is a thoroughly recrystallized foliated albite-epidote-actinolitic hornblende-chlorite rock with some quartz and muscovite. Sphene, partly altered to leucoxene, and magnetite are common accessory minerals. Relict phenocrysts of altered plagioclase, hornblende, and augite altered to epidote and chlorite are common. The phenocrysts of albite occur as 0.1- to 0.2-mm-long stubby laths that include small grains of epidote, chlorite, and muscovite. Hornblende phenocrysts are anhedral to subhedral and have sutured borders. A part of the epidote and chlorite occurs in clusters, some of which have relict outlines of augite. Most have lost their original shape. The foliation in the fine-grained groundmass usually bends around the altered phenocrysts.

Meta-andesite grades locally to lighter colored more siliceous metadacite and metasodarhyolite that are mineralogically and presumably chemically similar to their counterparts in the American House and Bucks Lake quadrangles (Hietanen, 1973a, 1976).

Fragmental meta-andesite with phenocrysts of augite, hornblende, and plagioclase occurs just west of the fault contact on the North Yuba River (loc. 2319), on the Fiddle Creek Ridge (loc. 2421), and east of Halls Ranch (loc. 2392). Plagioclase phenocrysts contain abundant alteration products, zoisite and leucoxene. The groundmass consists of albite, epidote, chlorite, and amphibole and is clouded by leucoxene. Some quartz occurs in the groundmass of a few fragments. Magnetite is a common accessory mineral.

On the north slope of Poverty Hill and north along Slate Creek (loc. 2448), meta-andesite grades to metabasalt that contains more hornblende and less epidote than the meta-andesite. Metabasalt is dark gray to black slightly foliated hornblende-albite-epidote-quartz rock that is transected by thin white veinlets of albite and epidote or of quartz. In some outcrops, white subhedral crystals of plagioclase (2 to 3 mm long) are scattered through the rock. Thin sections show that these phenocrysts have been altered to albite that includes grains of epidote and some small prisms of hornblende. The phenocrysts have preserved their subhedral outlines but were

granulated and recrystallized during the deformation. In most metabasalt, hornblende is pleochroic in bluish green and green and occurs as small subhedral to anhedral relict phenocrysts and tiny prisms; some are clustered. Large euhedral phenocrysts of very pale green to colorless hornblende with green rims are common in metabasalt on Slate Creek 0.5 km west of China Bar and to the south. The foliation in the groundmass bends around the phenocrysts. In contrast, the foliation butts against the cubes of pyrite, indicating that they are postkinematic. Epidote occurs in anhedral grains with albite, and in clusters between hornblende and albite; locally, it is segregated into layers parallel to the foliation. Some brown biotite, magnetite, and hematite occur as accessory minerals.

Chlorite and epidote with some calcite have crystallized instead of hornblende in some of the basaltic meta-andesite on Slate Creek (loc. 2447). In this rock, long subhedral phenocrysts of plagioclase include alteration products, epidote, muscovite, and some chlorite. Ilmenite surrounded by sphene and magnetite occur as accessory minerals.

A few layers in the basaltic meta-andesite have an exceptional texture. Albitic plagioclase, which makes up about 65 percent of the rock, occurs in small laths subparallel to the foliation, and hornblende and chlorite are interstitial. The percentage of epidote is lower (about 2 percent) than in common basaltic meta-andesite. Small grains of magnetite and leucoxene occur as accessory minerals. Calcite fills the fractures.

Meta-andesite west of the small body of hornblende quartz diorite in sec. 5, T. 19 N., R. 9 E. (loc. 2337) has recrystallized as hornblende gneiss with relict phenocrysts of plagioclase and hornblende. Epidote occurs in clusters of small grains or is scattered in the hornblende-rich layers. Magnetite partly altered to hematite forms thin irregular laminae and fills the cracks.

Layers of thin-bedded metatuff common in the eastern part of the Franklin Canyon Formation are exceptionally well exposed along Slate Creek and on Poverty Hill. Most of the metatuff is andesitic in composition; basaltic metatuff is interbedded with metabasalt on Poverty Hill and on Slate Creek. Layers having a dacitic or sodarhyolitic composition occur next to metadacite and metasodarhyolite, like, for example, west of La Porte (loc. 2093). Thin sections show that the andesitic metatuff consists of epidote, amphibole, chlorite, albite, and quartz in varying proportion. In the dacitic and sodarhyolitic metatuffs, there is more albite and quartz and less dark minerals and epidote. The basaltic metatuff is

rich in green hornblende and contains some albite, epidote, chlorite, quartz, leucoxene, and magnetite. In general, most of the metatuffs contain more quartz than the corresponding metavolcanic rocks, possibly as a result of weathering before the metamorphism, or perhaps some sedimentary material was deposited with the tuff. Lamination is common in much of the metatuff but is less regular than the lamination in metasedimentary rocks. The dark laminae consist mainly of amphibole, chlorite, and epidote. The light-colored laminae consist of quartz, albite, and some epidote. In some laminae, small laths of albite are embedded in a fine-grained mixture of quartz and albite.

Chemical analyses (table 1, anal. 2067, 2155) show that the meta-andesite west of La Porte is poor in potassium but contains a considerable amount of sodium, as is typical in early island-arc volcanic rocks (Jakes and White, 1972; Miyashiro, 1974). Stained specimens from the Franklin Canyon Formation rarely show potassium feldspar. An exception is a coarse-grained basaltic meta-andesite along Simon Ravine in the northern part of the Strawberry Valley quadrangle, 9 km south-southwest of La Porte. The chemical analysis of this rock (table 1, anal. 1589) shows 1.8 percent K_2O and only 1.22 percent Na_2O , the normative content of orthoclase being equal to that of albite (11 percent). It has been suggested on a structural basis (Hietanen, 1976, p. 5) that this rock may represent a former vent, somewhat younger than the more silicic western part of the Franklin Canyon Formation.

The large body of metavolcanic rocks on the west side of the Ramshorn fault consists mainly of porphyritic metadacite and metatuff that are petrologically similar to the rocks of the Franklin Canyon Formation. Thin sections show that in the metadacite phenocrysts of albite are embedded in groundmass of epidote, albite, quartz, amphibole, chlorite, and muscovite. The phenocrysts are 0.5- to 1-mm-long stubby laths oriented subparallel to the weak foliation. They include grains of epidote and tiny prisms of colorless amphibole. Albite grains in the groundmass are about 0.05 mm long and anhedral. Amphibole is in pale-green wispy prisms that include epidote and leucoxene. Epidote has recrystallized as subhedral to anhedral grains that are either clustered or occur as inclusions in albite, amphibole, and chlorite. Chlorite is pale grayish green and has a gray interference color.

Layers of interbedded metatuff are thin bedded, well foliated, and fine grained. The phenocrysts of albite are 0.01 to 0.05 mm long and rounded. They are embedded in a very fine grained matrix of albite,

quartz, epidote, chlorite, amphibole, and leucoxene.

BOULDERS OF META-ANDESITE WITH AUGITE PHENOCRYSTS

Meta-andesite with augite phenocrysts occurs as large scattered boulders (2 to 5 m in diameter) near the contacts of the Tertiary pyroclastic andesite and may form masses in areas now covered by the Tertiary extrusive rocks. These boulders are particularly common in the vicinity of the Little Grass Valley Reservoir (locs. 2193, 2095, 2099, 2282) and on the south and east side of the pyroclastic andesite on the Gibsonville Ridge (locs. 2033, 2068). Some (locs. 2068, 2099) are fragmental meta-andesite, the fragments consisting of the same kind of porphyritic rocks as most of the other boulders. Phenocrysts are either augite or augite and plagioclase. The groundmass is fine- to medium-grained mixture of albite, chlorite, epidote minerals, amphibole, magnetite, and leucoxene. Small phenocrysts of augite and tiny laths of albite are common in the groundmass. Olivine rimmed by pyroxene occurs in sample 2068. Amygdules are filled with quartz, epidote, calcite, or chlorite or with any two of these minerals.

The augite and plagioclase phenocrysts are euhedral to subhedral and have straight well-preserved crystal boundaries resembling in this respect the rocks of the Bloomer Hill Formation (Jurassic) in the Berry Creek quadrangle (Hietanen, 1977). The plagioclase phenocrysts include numerous grains of epidote and some sericite as alteration products. Augite in specimen 2099 has the optical properties

$$\alpha = 1.679(1), \beta = 1.686(1), \gamma = 1.702(1); +2V \sim 60^\circ.$$

MESOZOIC METASEDIMENTARY ROCKS

The phyllite and metachert in the southwestern part of the Goodyears Bar quadrangle west of the Ramshorn fault is less thoroughly recrystallized and less deformed than the rocks of the Calaveras Formation. The rocks between the Ramshorn fault and the eastern border of the meta-andesite of the Franklin Canyon Formation are metachert with subordinate phyllite, whereas in the western corner of the area, phyllite is the major rock type. Well-preserved radiolarians identified by David Jones, U.S. Geological Survey, as "Eptingium" twisted spines and nassellarian cones of Middle and Late Triassic age were obtained from a layer of metachert just west of the Ramshorn fault near the North Yuba River (loc. 2539). Metachert near the Dogwood Peak fault, 3.5 km northwest (loc. 2560, 2561, 2562), yielded

poorly preserved nassellarian cones and other unnamed forms of late Triassic to Early Jurassic age.

The contact between the early Mesozoic metachert west of the fault and the Franklin Canyon Formation is along the southern extension of the Dogwood Peak fault along and near Bow Creek. On Fiddle Creek Ridge, the metachert with a vertical bedding is exposed on higher parts of the ridge, the metaandesite below it in the canyon of Fiddle Creek. The fault contact dips about 60° to the east. Most of the metachert on higher parts of the ridge is recrystallized to fine-grained dark-to light-gray rock with micaceous laminae and phyllitic layers. Poorly recrystallized gray to black layers are common along the North Yuba River and locally at higher altitudes. Thin sections made of black phyllite show tiny angular scattered grains of quartz in gray opaque matrix in which some chlorite, muscovite, and epidote can be identified, but much of the rock is colored dark by disseminated iron oxides and carbon.

The contacts between the phyllite in the southwest corner of the area and the metavolcanic rocks of the Franklin Canyon Formation appear to interfinger, and layers of metavolcanic rocks are interbedded with phyllite along the North Yuba River in sec. 10 and 11, T. 19., R. 9. E. Mapping of the area south of the North Yuba River would be necessary to determine true structural relations. In the outcrop, this phyllite differs from the phyllite of the Calaveras Formation in many respects. Most layers consist of very fine grained dark-gray to black rock with a poorly to moderately developed foliation. Bedding is well preserved and is accentuated by layers of interbedded metachert and cherty phyllite, both fine grained and black.

Thin sections show every gradation from black phyllite to pebbly phyllite in which pebbles are metachert and further to metachert with micaceous laminae. The black color is imparted by abundant disseminated iron oxides and carbon. Micaceous minerals, tiny flakes of muscovite and biotite with sparse chlorite, are parallel to the foliation which bends around the oval to subangular grains of quartz. Prehnite fills the cracks in metatuff interbedded with phyllite at location 2349.

A layer of phyllite, about 1 km wide, extends 8 km northward from the North Yuba River on the east side of the Indian Valley pluton. It is bordered by the metavolcanic rocks of the Franklin Canyon Formation and by the plutonic rocks that have narrow contact aureoles. Most of this phyllite is strongly deformed. It has well-developed foliation and two sets of lineations, the *b* lineations parallel to the fold

axes and the *a* lineation perpendicular to it in the plane of foliation. A wrinkling on the *b* axes is common. The bedding is well preserved and is accentuated by interbedded thin layers of quartzite and metatuff.

A layer of phyllite that extends northwest from the Indian Valley pluton is much less deformed. The bedding is excellently preserved, but the foliation is barely discernible. Some layers of this rock at the western border of the quadrangle contain small spheroids (1 mm long) that either stand out on the weathered surfaces or have fallen off leaving cavities. Thin sections show that these spheroids consist of the same minerals, quartz and biotite, as are present in the main part of the rock. They may be traces of raindrops or remnants of fossils, but because of a complete recrystallization they cannot be identified. In some layers, a part of the biotite occurs in subangular flakes that are larger than the grains of other minerals. This texture resembles that of the contact metamorphic hornfels rather than tectonite.

A layer of black phyllite, similar to that along the North Yuba River is interbedded with the metavolcanic rocks of the Franklin Canyon Formation south of Poverty Hill. Biotite is the most common micaceous mineral in this phyllite. Toward the border zones, it contains thin layers of tuffaceous material, which consists either of light-green hornblende and albitic plagioclase or of quartz, plagioclase, biotite, hornblende, and disseminated magnetite.

AMPHIBOLITE AND ASSOCIATED METAVOLCANIC ROCKS

Amphibolite is exposed in the canyons of Slate Creek and Canyon Creek in the northeastern half of the La Porte quadrangle and to the north in the canyons of the South Fork of the Feather River and Onion Valley Creek. The outcrop pattern suggests that the mass is semicircular in shape with a large central "inclusion" of quartzite and schist that resembles the Shoo Fly Formation. The amphibolite is strongly foliated hornblende-plagioclase (An₃₀)-quartz-epidote-sphene rock with a unique texture: the hornblende occurs in long prisms that have their *c* axis aligned parallel to a strong lineation in the plane of foliation (fig. 6A). The *b* axes of the hornblende prisms are perpendicular to the lineation in the plane of foliation, the *a* axes perpendicular to both the lineation and foliation (fig. 6B). Lamination parallel to the foliation is common, and much of the amphibolite has a gneissic texture caused by segregation of plagioclase, quartz, and epidote into thin layers. The orientation of the foliation and lineation is an

internal feature unrelated to the regional structures. Foliation tends to be parallel to the contacts dipping 50° to 80° outward. Lineation is generally down the dip on the planes of foliation. Orientation of these structural elements is most likely primary, formed by crystallization and subsequent recrystallization of the constituent minerals during the emplacement of the basaltic magma under hypabyssal conditions.

In the amphibolite, a fracture cleavage and wrinkling on the northwest-trending axes are superimposed on the planes of foliation. In most outcrops, these late structural features are rather weakly developed and can be observed only in reflected light. Their parallelism with the regional trends indicates that the amphibolite was emplaced before the Jurassic Nevadan orogeny, during which all pre-Jurassic rocks were deformed.

The potassium-argon age on hornblende in the amphibolite determined by Fred K. Miller, U.S. Geological Survey, is 248 m.y. ($Ar^{40}_{rad}=10.78 \times 10^{-10}$ mol/g, 0.281 percent K_2O , 82 percent Ar^{40}_{rad}). This Permian age for an intrusive body cutting the Calaveras Formation confirms the Pennsylvanian age for the Calaveras Formation in this area.

The texture of the amphibolite contrasts with the texture common in metagabbro and metadiorite in this area. Hornblende and other mineral grains in these metamorphosed plutonic rocks are equant in shape, have irregular outlines and no appreciable orientation. Foliation in them is weak to moderate and parallels the north or northwest trends. Lineation, if present, is parallel to the regional fold axes.

The circular shape texture, and internal structure pattern of the amphibolite are suggestive of a dome-shaped mass associated with a volcanic neck having a collapsed caldera or cauldron and cut on the east side by the Melones fault. It may have been a channel for eruption of some of the metavolcanic rocks such as those exposed south of it along Canyon Creek and on Reese Ravine.

An elongate sill-like body of mineralogically and structurally similar amphibolite occurs in the Shoo Fly Formation on the northeast side of the Melones fault in the north-central part of the Onion Valley quadrangle, continuing to the southern part of the Quincy quadrangle. This body is well exposed on ridges northwest and south of Claremont and along the road to Egbert Mines south of Crescent Hill. Burnett and Jennings (1962) show the narrow south end of this body at Minerva Bar on the Middle Fork of the Feather River. Most of this amphibolite is somewhat finer grained than the large round mass, and there is no metavolcanic border zone. Instead there is a narrow chlorite-bearing border zone that probably represents an altered contact zone of the sill.

Comparison of chemical analysis of the amphibolite in this sill (table 1, anal. 2592) with that in the large round body (table 1, anal. 2043) shows a higher content of SiO_2 , Al_2O_3 , and CaO and a lower content of FeO in the sill near Claremont.

The chemical composition of hornblende in the amphibolite specimen 2043 (table 2, anal. 2043h) is similar to that of the hornblende in the metabasalt in

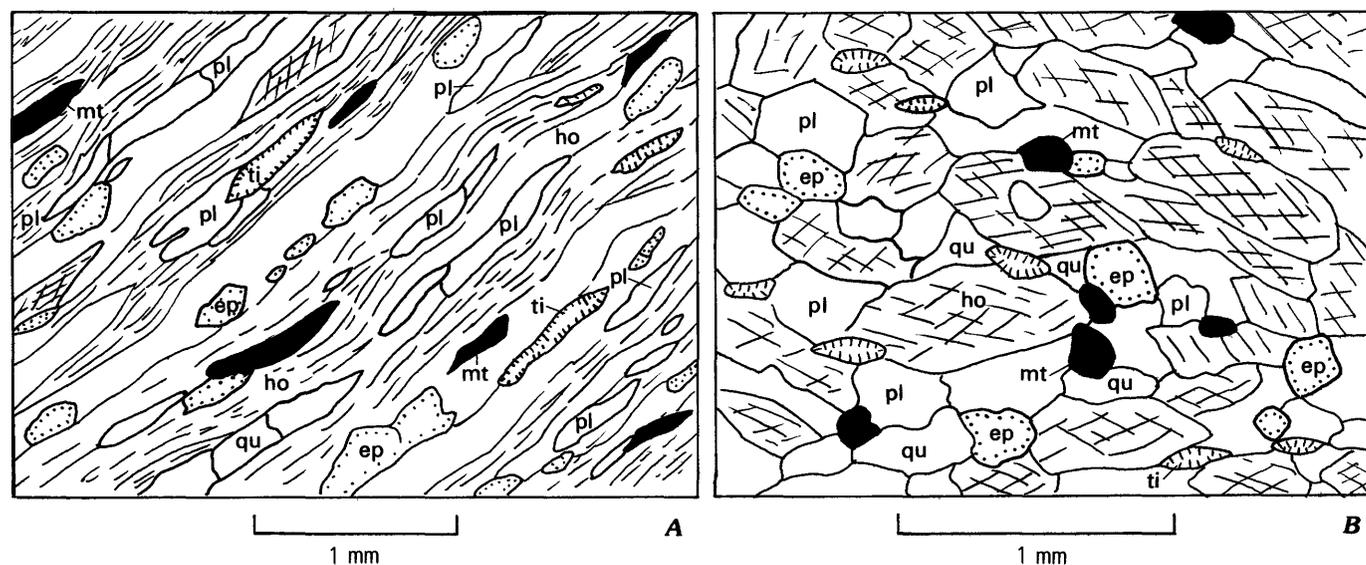
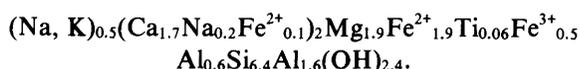


FIGURE 6.—Sketches showing textures in amphibolite; ho=hornblende, ep = epidote, pl = plagioclase, qu = quartz, ti = sphene, mt = magnetite. A, Thin section parallel to lineation but perpendicular to plane of foliation shows longest and shortest dimensions of amphibole prisms. B, Thin section cut perpendicular to lineation shows cross sections of amphibole prisms. The *b* axes of amphiboles are parallel to foliation.

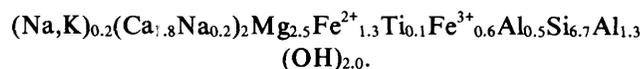
the Bucks Lake quadrangle except for a somewhat higher sodium and lower calcium content. The calculated formula shows about equal number of Mg and Fe²⁺ ions, 1.57 tetrahedral Al and 1.1 octahedral Al+Fe³⁺. With 0.06 Ti⁴⁺, the tschermakitic substitution (Al^{VI}Al^{IV} ≅ Mg^{VI}Si^{IV}) is about 1.2. The A site occupancy is 0.53, and the edenitic substitution (Na^AAl^{IV} ≅ □^ASi^{IV}) about 0.5. The ratio between these two types of substitution is similar to that in the hornblendes in the Bucks Lake quadrangle (Hietanen, 1974). The glaucophanitic substitution Na^{M4}Al^{VI} ≅ Ca Mg is about 0.2. The generalized formula is



In Leake's classification (1978), it falls into ferroan pargasitic hornblende group. The indices of refraction of this hornblende are

$$\alpha = 1.661(1), \beta = 1.674(1), \gamma = 1.683(1).$$

For comparison an optically similar green hornblende from a metagabbro in an ophiolite sequence along Slate Creek, 5 km west of the Scales pluton, was analyzed chemically (table 2, anal. 2637h). This hornblende has a lower Al, Fe²⁺, and Na content and a higher Mg content than the hornblende in the amphibolite, reflecting a higher magnesium content of the host rock. Calculation of the analysis 2637h on the basis of 23(O) yields the generalized formula



The amphibolite is bordered on the south, southwest, and northeast by a 500-to 600-m-thick layer of metavolcanic rocks that consist mainly of thin-bedded basaltic metatuff and include some sedimentary material. These rocks are well exposed on Canyon Creek west of Poker Flat, near the Monumental Mine on the north side of Canyon Creek, along Slate Creek east of French Camp, and along Onion Valley Creek and its tributaries. In all localities, the bulk of the rocks are thin-bedded metatuff rich in hornblende and epidote and contain plagioclase (An₂₈), chlorite, sphene, magnetite, and some quartz, biotite, and rutile. Pillow structures are exposed in locality 2261 along Canyon Creek. Near the mouth of Deadwood Creek, a fault separates the amphibolite from the Calaveras Formation. A fault breccia is well exposed on the ridge north of Deadwood Creek (loc. 2242).

The contact of the amphibolite and its thin-bedded

border zone is well exposed on Canyon Creek west of Poker Flat. The rock next to the strongly lineated amphibolite has a weak lineation but distinct foliation and obscure bedding. Thin sections show that this rock consists of layers rich in either hornblende or epidote. The hornblende is pleochroic in light bluish green (γ), green (β), and very light green (α) and is well oriented parallel to the foliation. Small grains of epidote and brown rutile occur with hornblende. The epidote-rich layers are thin and discontinuous and consist of large grains of epidote, plagioclase (An₃₀), quartz, and small prisms of hornblende. Distinctly bedded metatuff and layers of metaandesite occur farther from the contact.

Near the Monumental mine, thin layers of biotite-muscovite phyllite are interbedded with metatuff, suggesting that some sedimentary material was here deposited with the tuff. A few thick layers in metatuff exposed on Slate Creek and Canyon Creek contain volcanic bombs of basaltic composition. On Canyon Creek such layers are south of pillow lava exposed southeast of the Monumental mine (loc. 2261). Both the metatuff containing volcanic bombs and the pillow lava, 30 m thick, are separated by faults from the metachert of the Calaveras Formation to the south.

Thin sections show that the bombs in the metatuff consist of green hornblende, epidote, plagioclase (An₂₈), sphene, magnetite, and ilmenite, essentially of the same minerals as constitute the enclosing metatuff. Chemical analysis (table 1, anal. 2106) shows that the volcanic bombs along Slate Creek contain much less iron and more calcium than the amphibolite (table 1, anal. 2043). This is mineralogically indicated by a larger amount of epidote present in the bomb. The pillow lava contains even less hornblende and more epidote than the analyzed bomb and thus has an andesitic composition.

On Onion Valley Creek and its tributaries, the rocks bordering the amphibolite consist of interbedded layers rich either in quartz and chlorite (metasedimentary) or in hornblende and epidote (tuffaceous). In the eastern border zone, layers of thin-bedded fine-grained light-gray quartzite are exposed in the middle of the section. Thin sections show that some thin layers in chlorite schist contain calcite, some others are rich in quartz, and a few are fragmentary, resembling lithic metagraywacke. Fragments are made up of anhedral grains of quartz and some interstitial chlorite and calcite. The hornblende-rich layers consist mainly of very light green hornblende, epidote, albite, quartz, chlorite, and scattered grains of either sphene or brown rutile, magnetite, and occasional muscovite. The horn-

blende is pleochroic in light bluish green (γ), light green (β), and very light green to colorless (α). Prisms are long and slender and well oriented parallel to the foliation. A brecciated hornblende-rich layer on Onion Valley Creek (loc. 2498) contains large skeletal magnetite grains and aggregates of quartz. In most outcrops, bedding is distinct, and the foliation is parallel to it. Small folds can be observed in some schist outcrops, and in these foliation is parallel to the axial planes.

METAMORPHOSED INTRUSIVE ROCKS

Metamorphosed intrusive rocks occur as small elongate masses and dike-like bodies in the metasedimentary and metavolcanic rocks. They range in composition from mafic gabbro through quartz diorite and tonalite to trondhjemite and exhibit various degrees of deformation. Small masses of metagabbro and tonalite are particularly common along the fault zones and within or next to the serpentine bodies.

In small gabbroic masses, as at locations 2285 and 2364, green hornblende in subhedral to wispy prisms is the major constituent (about 65 percent). Plagioclase is albitic and includes, in addition to the alteration products zoisite and epidote, some small hornblende crystals and leucoxene. Large grains of epidote occur within and next to the hornblende. Magnetite and ilmenite occur as accessory minerals. Some of the larger masses such as the one north of Onion Valley Creek are gneissic and contain about 50 percent plagioclase.

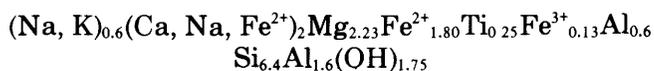
A small mass of pyroxene gabbro and diabase exposed on Little Canyon Creek (loc. 2240) just west of the purplish-gray meta-andesite (loc. 2237) may represent a volcanic vent for metabasalt and meta-andesite. The diabase is greenish gray and fine grained and has some dark seams parallel to a weakly developed foliation. Toward the west, it grades into a medium-grained pyroxene gabbro.

Thin sections of the diabase show that it consists of plagioclase and augite in about equal amounts. The plagioclase laths include abundant zoisite and some chlorite and are clouded by leucoxene. Interstitial augite is well preserved. Round aggregates consisting of fine-grained very light green chlorite with brownish-gray to very dark gray interference color are probably pseudomorphs after olivine. Accessory minerals, sphene and ilmenite, have altered partly to leucoxene that includes small grains of magnetite. Fractures are filled with chlorite, amphibole, and quartz.

Pyroxene gabbro is much coarser grained than the diabase and contains more chlorite. Some of the

chlorite is in interstitial aggregates; some is clustered with augite to form ultramafic patches in coarse-grained diabasic gabbro. Ilmenite has altered to leucoxene. Some slender amphibole prisms are next to augite, and a few are included in chlorite aggregates.

Small masses of altered gabbro, presumably parts of an ophiolite sequence, are exposed within and next to the Melones fault zone. In the Downieville quadrangle, several masses are on the east side of the ultramafic rock that parallels the Goodyears Creek fault. The northernmost of these (loc. 2371) consists of medium-grained dark-gray slightly foliated hornblende-pyroxene gabbro with a granoblastic texture. In the hand specimen, black hornblende, which constitutes about 60 percent of the rock, contrasts against the white to light-bluish-gray plagioclase. Thin sections show that the major dark mineral is brown hornblende and that diopside and chlorite occur in small amounts. All these minerals as well as plagioclase occur as polygonal grains, typical in norites. The hornblende is strongly pleochroic in reddish brown (γ , β) and light brown (α); the indices of refraction ($\alpha = 1.663(1)$, $\beta = 1.691$, $\gamma = 1.707(1)$) are higher than those of the green hornblende. Extinction angle $\gamma \Delta c = 8^\circ$ to 14° . Chemical analysis (table 2, anal. 2371h) shows that its composition is similar to that of the green ferroan pargasitic hornblende in the amphibolite (anal. 2043h) except for less Fe_2O_3 and more TiO_2 and MgO . The generalized calculated formula is



Diopside is colorless to very pale green and has

$$\alpha = 1.693(1), \beta = 1.701(1), \gamma = 1.717(1).$$

Chemical analysis (table 2, anal. 2371d) shows a low aluminum content and a high magnesium:iron ratio as typical of diopside. The calculated formula



shows that it is mainly diopside with some hedenbergite and ferrosilite. The percentages of the end members are: diopside 62, hedenbergite 16, ferrosilite 13, jadeite 4, and FeAl_2O_4 5.

The large polygonal grains of pale-green chlorite were probably orthopyroxene originally. Some of these grains show fine twinning lamellae reminiscent of the twinning common in orthopyroxenes. Small flakes of chlorite are common along the cracks. Plagioclase is altered to zoisite and clouded gray by leucoxene.

Chemical analysis of this metagabbro (table 1, anal. 2371) shows that it is richer in magnesium, calcium, and aluminum than the amphibolite (anal. 2043). There is also a marked difference in trace element content of these two mafic intrusive rocks, the metagabbro containing considerably more barium, copper, nickel, and vanadium.

The potassium-argon age on hornblende in this metagabbro (loc. 2371) is 285 ± 8 m.y., determined by J. L. Morton, U.S. Geological Survey (data: $Ar^{40}_{rad} = 6.285 \times 10^{-11}$ mol/g; 0.142 percent K_2O ; 50 percent Ar^{40}_{rad}). This metagabbro was thus emplaced earlier than the round large amphibolite mass. These two mafic rocks could, however, be differentiates of similar basaltic magmas generated in the oceanic lithosphere, within or near the active subduction zone.

A much older age (387.4 ± 6.7 m.y.) was reported by Standlee (1978) on hornblende from dikes cutting cumulate to massive mafic and ultramafic igneous rocks along the Melones fault near Onion Valley. This age would indicate that the tectonic and igneous activity along the Melones fault started in the Devonian.

Brown hornblende is a major constituent in metagabbro at locality 2366. In this rock, augite is segregated into light-greenish-gray plagioclase-rich schlieren included in dark-gray hornblende-plagioclase rock. Plagioclase is altered to zoisite and muscovite. Plagioclase, quartz, and tiny needles of colorless amphibole occur along joints. Elongate grains of magnetite and sphene are common accessory minerals.

Metagabbro along the Melones fault 1.5 km north-northwest of Downieville is strongly sheared and altered. Rounded brown hornblende crystals are embedded in a fine-grained mixture of granulated plagioclase, tremolite, chlorite, and zoisite. The gabbro is transected by veinlets of quartz and quartz plus albite that include needles of tremolite.

A small mass of pyroxene gabbro is exposed next to serpentine on headwaters of Old Mill Creek in the Mount Fillmore quadrangle (loc. 2358). The serpentine marks the northern continuation of the Good-years Creek fault in this vicinity and is exposed only along the creek. The gabbro is coarse grained and consists of green augite and dull light-gray plagioclase. Thin sections show that subhedral plagioclase crystals are altered to aggregates of fine-grained zoisite and are clouded by leucoxene. Augite is in anhedral fresh grains. In places, colorless needles of secondary tremolite are included in albitic plagioclase or form seams between the plagioclase and augite. Some vugs are filled with pale-green chlorite and celadonite.

Gabbroic rock next to serpentine on the south side of Reese Ravine (loc. 2359) consists of prisms of pale-green to colorless actinolitic hornblende and interstitial epidote in about equal amounts. The fractures are filled with oligoclase (An_{27}); some quartz, sphene, magnetite, and hematite occur as accessory minerals.

In the northern part of the area, small masses of metagabbro are exposed next to and near the ultramafic rocks along the Melones fault and on the west side of the large Feather River ultramafic body. The largest of these extends more than 2 km parallel to the regional trends and is about 250 m thick where Onion Valley Creek crosses it. The steep outcrops along this creek consist of well-foliated medium-grained hornblende-plagioclase rock. A gabbroic dike in serpentine northeast of this large mass has a composition similar to the main mass but the hornblende prisms are long and slender and in a random arrangement, as typical in dikes. Sphene and magnetite occur as accessory minerals, and plagioclase (An_{30}) includes alteration products, sericite and epidote.

The metagabbro mass west of Onion Valley (loc. 2578) is layered and transected by dikes. On the north side of Onion Valley Creek, the lower, southeastern part consists of layered metagabbro, some of it coarse grained, and the upper, northwestern part of tonalite. The southern part of the sill south of Onion Valley Creek is metadiorite. The metagabbro consists mainly of pyroxene, hornblende, and clinzoisite with some chlorite, plagioclase (An_{30}), and magnetite.

The metagabbro south of the Middle Fork of the Feather River (loc. 2601) is medium-grained plagioclase (An_{28})-augite-hornblende-magnetite rock with some secondary chlorite and a brown micaceous mineral (stilpnomelane?). Plagioclase forms elongate subhedral crystals that include alteration products, sericite and epidote. Augite, the main dark constituent, forms large anhedral grains that include subhedral crystals of magnetite. Green hornblende is partly rimmed by small prisms of light-bluish-green actinolite. Most of the stilpnomelane forms aggregates and radiating clusters next to the magnetite and hornblende.

A small elongate mass consisting mainly of altered porphyritic hornblende quartz diorite and some gabbroic diorite is exposed along a ridge that extends from the Lucky Hill mine northwestward toward Slate Creek (loc. 2132). The border zones of this mass are strongly foliated quartz diorite in which subhedral elongate and twinned plagioclase phenocrysts and large anhedral hornblende crystals are embedded in a medium-grained groundmass of

epidote, hornblende, chlorite, plagioclase, quartz, muscovite, and accessory minerals, magnetite and leucoxene. Plagioclase phenocrysts include small grains of epidote and muscovite. The gabbroic part of this sill-like body contains euhedral to subhedral stocky hornblende phenocrysts (2 to 6 mm long), in a medium-grained groundmass consisting mainly of plagioclase, epidote, hornblende, chlorite, and leucoxene. The porphyritic texture and a large amount of epidote in this rock are reminiscent of basaltic meta-andesite with hornblende phenocrysts. This sill-like body is genetically similar to the metadiorite and metagabbro in the neighboring American House quadrangle (Hietanen, 1976).

A dike of fine-grained dark-gray metagabbro exposed in a roadcut on the west border of the Goodyears Bar quadrangle (loc. 2291) consists of light-green hornblende (50 percent), plagioclase, epidote, quartz, and leucoxene. Plagioclase is in small laths that are in a random arrangement and show Carlsbad, albite, and complex twinnings and include small grains of epidote, hornblende, and leucoxene. Ilmenite and sphene are altered to hematite and leucoxene.

A dike of foliated fine-grained hornblende gabbro with scattered small plagioclase phenocrysts cuts the metavolcanic rocks on the east side of Poverty Hill (loc. 2444). The groundmass in this dike consists of bluish-green hornblende, albitic plagioclase, epidote, magnetite, and ilmenite. Similar dikes are exposed along Slate Creek north of Poverty Hill where they cut metabasalt.

Quartz dioritic dikes on North Yuba River (loc. 2331) consist of plagioclase (about 60 percent), hornblende (30 percent), biotite (8 percent), quartz, magnetite, and hematite. Most of the plagioclase and some of the hornblende is in large subhedral crystals embedded in a fine-grained groundmass of hornblende needles, biotite, plagioclase, and quartz. Plagioclase includes small prisms of hornblende, some biotite, and a few tiny grains of epidote.

In a typical quartz dioritic dike, slender prisms of hornblende in a random arrangement and some subhedral plagioclase laths occur as phenocrysts. The groundmass consists of smaller prisms of hornblende and interstitial plagioclase, quartz, and chlorite (for example, loc. 2104). Small grains of epidote are included in plagioclase. Sphene and magnetite occur as accessory minerals.

A porphyritic dike with phenocrysts of albite and clusters of chlorite cuts the schist near the west border of the Onion Valley quadrangle (loc. 2504). The groundmass consists of albite, epidote minerals, chlorite, quartz, and magnetite and includes small

prism-shaped aggregates of chlorite and epidote in a random arrangement, probably originally hornblende prisms that are common in less altered dikes.

A small mass and several dikelike bodies of coarse- to medium-grained greenish-gray porphyritic tonalite are exposed within the serpentine on Onion Valley Creek near the Williams and Dorf mine (loc. 2440). Phenocrysts in this rock are plagioclase and hornblende. The plagioclase phenocrysts are 1 to 3 mm long and are altered to muscovite and epidote. The hornblende phenocrysts are small (0.5 to 2 mm long) and pleochroic in green and pale green. The groundmass is fine grained and consists of quartz, plagioclase, epidote, hornblende, muscovite, and chlorite. A few tiny grains of calcite and magnetite occur as accessory minerals.

Metamorphosed dikes of basaltic and andesitic composition are common in the Calaveras Formation. Most of these dikes are 1 to 6 m wide and extend only a short distance parallel to the foliation. Dikes of fine-grained meta-andesite or of metabasalt are common near the equivalent volcanic rocks. For example, an andesitic dike, 4 m wide, exposed on Little Canyon Creek (sec. 31, T. 21 N., R. 9 E.) is mineralogically similar to the nearby meta-andesite and is probably genetically associated with it. Basaltic meta-andesite dikes west of the metabasalt and meta-andesite on Reese Ravine and on Old Mill Creek along the western border of the Mount Fillmore quadrangle are probably comagmatic with the metabasalt and meta-andesite.

An altered diabasic dike is exposed on the south side of Deadwood Ravine (loc. 2215). This dike consists of long laths of plagioclase that are granulated and altered to muscovite. Interstitial dark minerals have altered to a mixture of chlorite, zoisite, iron oxides, and leucoxene.

Andesitic dikes containing sheared and partly altered augite phenocrysts are parallel to the foliation in muscovite phyllite in the south-central part of the La Porte quadrangle (locs. 2217, 2218). The fractured and sheared phenocrysts of augite are partly altered to amphibole and chlorite. The groundmass is foliated and consists of a fine-grained mixture of albite, muscovite, and epidote clouded by leucoxene. Narrow veinlets of quartz and calcite with border zones of chlorite cut this metamorphosed dike rock.

Porphyritic dike rock containing large subhedral phenocrysts of augite is exposed at the headwaters of Morris Ravine on the south side of Port Wine Ridge (loc. 2091). Thin sections show that the augite is partly altered to amphibole and chlorite. Plagioclase occurs as small phenocrysts that include tiny grains

of epidote. The groundmass consists of epidote, amphibole, chlorite, albite, quartz, magnetite, and leucoxene.

ULTRAMAFIC ROCKS

Elongate bodies of ultramafic rocks at various stages of serpentinization occur along the major fault zones, the Melones, Goodyears Bar, and Ramshorn faults. These ultramafic rocks originated in the mantle and were brought up during the tectonic events and subsequently serpentinized. The largest body is exposed in the central part of the Onion Valley quadrangle. In the Mount Fillmore quadrangle, Tertiary pyroclastic rocks cover much of the Melones fault zone. The ultramafic rocks, mainly serpentine, are exposed only fragmentarily on the slopes and in the canyons. Farther south, serpentine is exposed continuously along Goodyears Creek and on its eastern slope. The major rock type along the Ramshorn fault is a strongly sheared moss-green serpentine and soapstone.

The ultramafic body that occupies most of the Onion Valley quadrangle (pl. 1) is the southern part of the large Feather River ultramafic body that in the Bucks Lake quadrangle is bordered by the Melones fault in the northeast and by the Rich Bar fault in the southwest (Hietanen, 1973a). The North and Middle Forks of the Feather River and their tributaries cut deeply into this ultramafic mass, providing good exposures. At higher altitudes, much of it is covered by Tertiary pyroclastic rocks. In the southernmost part of the Onion Valley quadrangle, the southern tip of this large mass penetrates the circular mass of the Permian amphibolite, and only narrow masses of ultramafic rocks accompany the Melones fault that is 2 to 3 km farther east.

Most of the Feather River ultramafic body in the Onion Valley quadrangle is lherzolite that is only partly serpentinized. Good exposures along Onion Valley Creek (loc. 2495) and on the southwest slope of Washington Creek (loc. 2438) show primary layering that makes an angle with the regional trends. In both localities, the rock consists of olivine (55 to 70 percent), pyroxene (enstatite and clinoenstatite), colorless magnesian hornblende, serpentine minerals, and magnetite. Olivine grains are elongate (1 to 3 mm long) and clustered into irregular lensoid aggregates parallel to a crude layering. The intervening irregular layers and lenses consist of pyroxene, most of it altered to colorless hornblende and large grains of antigorite (bastite). Pyroxene is mainly enstatite, but remnants of clinopyroxene are included in hornblende. Enstatite grains are altered to bastite parallel

to their cleavage planes.

Olivine is transected by irregular cracks that are filled with serpentine and magnetite. In addition, olivine aggregates, but not the secondary hornblende and bastite, are traversed by wider seams of serpentine and magnetite parallel to the crude layering (s_1). The cleavages in the secondary minerals tend to be parallel to the s_2 plane that makes an angle with the layering. These relations show that the layering was produced by aggregation and crystal settling during the crystallization, at depth, of primary constituents, olivine and pyroxenes, and that the secondary hornblende and bastite crystallized late, after the serpentinization of olivine along the cracks. In more thoroughly serpentinized rock, the relations are obscured and the sequence of events is lost. The orientation of the primary layering is not related to the regional trends; this supports the concept that the ultramafic rock was emplaced as a solid mass. It most likely originated in the upper part of the mantle and was brought up by tectonic movements along the Melones fault.

The brown-weathering ultramafic rock on the south side of the Middle Fork of the Feather River consists of about 75 percent serpentinized olivine, 24 percent secondary amphibole and bastite, and very little unaltered pyroxene. The network of serpentine-filled cracks in olivine occupies three to four times the volume of unaltered olivine. With advanced serpentinization, all traces of primary layering are lost.

RODINGITE

Serpentine along the Melones fault and the Ramshorn fault include dikelike bodies and round masses of fine-grained light-gray to white hydrous calc-silicate rock, rodingite, in which the major constituents are hydrogarnet, vesuvianite, diopside, and chlorite. The name rodingite was proposed by Marshall (in Bell and others, 1911) for mineralogically similar rocks on the Roding River, Dun Mountain area, New Zealand. Earlier similar calc-silicate rocks consisting mainly of grossularite-andradite, diopside, epidote, vesuvianite, chlorite, and prehnite in the western Italian Alps had been described under the name "granatite" and considered by most workers to be contact-metamorphosed calcareous intercalations. Their identity with rodingites was pointed out by Dal Piaz (1967), who agreed with Franchi (1895) that like most rodingites described from various localities around the world, they were derived from gabbroic dikes and inclusions (rarely from the other rocks) by metasomatic transformation

(Arshinov and Merenkov, 1930; Miles, 1950; Bloxam, 1954; Bilgrami and Howie, 1960; Vuagnat, 1965; Coleman, 1966, 1967; Bassaget and others, 1967; Bezzi and Piccardo, 1969; Alberti and others, 1976).

In the study area of this report, an early stage of metasomatic transformation of a gabbroic dike into rodingite is evident in a dike 0.5 km east of Lake Delahunty. In hand specimen, this rock is similar to metagabbro except for a lighter and somewhat milky color. Thin sections show that it consists of colorless to very light green amphibole (60 percent), zoisite, epidote, albite, chlorite, and hydrogarnet. The hydrogarnet is interstitial and encloses other minerals, giving an impression that it crystallized later than the other constituents.

A thoroughly transformed dikelike body with a relict texture reminiscent of gabbroic dikes is exposed on a small hill about 0.25 km west of Lake Delahunty at the southern border of the Onion Valley quadrangle (loc. 2118). This dike is fine-grained light-pinkish-gray rodingite in which the major constituents are hydrogarnet, vesuvianite, diopside, and chlorite. Without crossed nicols, the texture is similar to that of the gabbroic dikes in this vicinity. The light-colored areas that have the shape of subhedral plagioclase laths in unaltered gabbro dikes now are mainly isotropic hydrogarnet. The dark minerals have been replaced by a mixture of vesuvianite, diopside, and chlorite, all clouded by leucoxene. In accordance with these replacements, the chemical analysis of this rock (table 3) shows an exceptionally high content of calcium and a lower content of silicon, iron, magnesium, and sodium than is common in metagabbro in this area (compare for example, anal. 2371, table 1).

TABLE 3.—*Chemical composition and trace elements of rodingite*
[Chemical analysis by Sarah T. Neil; spectrographic analysis by M. L. Retzliff]

Weight percent	Cation percent	Molecular norm
SiO ₂.....37.79	SiO ₂.....36.91	Orthoclase.....05
TiO ₂.....1.42	TiO ₂.....1.05	Albite.....2.20
Al ₂ O ₃.....14.53	AlO _{3/2}.....16.73	Anorthite.....41.66
Fe ₂ O ₃.....4.50	FeO _{3/2}.....3.31	Wolla.....13.32
MnO......14	MnO......12	Fayalite.....1.44
MgO.....6.10	MgO.....8.88	Larnite.....16.72
CaO.....28.00	CaO.....29.30	Magnetite.....4.96
Na ₂ O......02	NO _{1/2}......04	Ilmenite.....2.08
K ₂ O......01	KO _{1/2}......02	Apatite......19
P ₂ O ₅......08	PO _{3/2}......07	Calcite......18
CO ₂......07	CO ₂......10	Total.....100.00
H ₂ O.....2.52	OH.....(16.42)	
H ₂ O......20	Total.....100.00	
Total.....99.69	Total anions.....156.32	
	KO _{1/2}= 0.248	
	KO _{1/2} +NaO _{1/2}	
Trace elements, in parts per million		
B.....9	Ca.....120	Y.....50
Ba.....80	Ni.....100	Zn.....72
Be.....3	Sc.....71	Zr.....210
Co.....75	Sr.....20	Ga.....30
Cr.....230	V.....430	Yb.....7

On the north side of North Yuba River north of Ramshorn Campground (loc. 2365), 20- to 50-cm-long lenses of fine-grained white rodingite are enclosed in strongly sheared serpentine. These lenses are mineralogically similar to the rodingite dike near Lake Delahunty, but there are no relict textures that would indicate the nature of the original rock type. It may well have been a gabbroic dike that was boudinaged during a strong deformation evident in the surrounding serpentine. Thin sections show a fine-grained mixture of vesuvianite, chlorite, diopside, and hydrogarnet. Identification of minerals in both specimens (locs. 2118 and 2365) was verified by X-rays by Julius Schlocker, U.S. Geological Survey, who also determined the unit cell of hydrogarnet as $a_0 = 11.83 \text{ \AA}$ in specimen 2118 and $a_0 = 11.998 \text{ \AA}$ in specimen 2365.

Transformation of gabbroic rocks into rodingite requires a considerable addition of calcium and removal of silicon and alkalis. The source of added calcium is generally believed to be the surrounding peridotite, in which calcium is released from diopside and hornblende during the serpentinization (Bilgrami and Howie, 1960; Vuagnat and Pusztaszeri, 1964; Coleman, 1966, 1967; Dal Piaz, 1967, 1979; Galli and Bezzi, 1969; O'Brien and Rogers, 1973). Bilgrami and Howie (1960) observed that the dikes that cut serpentine were transformed to rodingite, whereas the dikes in the fresh peridotite were not altered. Dal Piaz (1967) suggested that the transformation of primary gabbroic rock into rodingite is proportional to the degree of serpentinization of the enclosing peridotite.

A typical partly serpentinized peridotite in the Feather River area contains about 2.3 percent CaO, most of it in primary hornblende and diopside (Hietanen, 1973a, tables 1 and 2). When the calcium was released during the advanced serpentinization of small bodies, it migrated outward, forming seams of tremolite along the contacts. At a few localities within large masses where serpentinization has advanced to a complete destruction of primary minerals, small scattered aggregates of hydrogarnet and secondary amphibole are included in serpentine, as at locality 395 in the Bucks Lake quadrangle (Hietanen, 1973a, p. 27-28). This advanced serpentinization and late stage reactions took place during the regional metamorphism, whereas the rodingitization of the gabbroic dikes probably started during the early stage of serpentinization, as soon as the ultramafic masses had ascended from their stable mantle environment into the lower crust. Gabbroic magmas that form stably at this level had invaded the tectonically weakened zones in the ultramafic

masses. During the further ascent of the now diked ultramafic masses, serpentinization continued and the calcium released in this process migrated into the included gabbroic dikes, causing their rodingitization.

This view of early deep-seated beginning of rodingitization is supported by a recent find of rodingites in the walls of the fracture zones of the equatorial mid-Atlantic Ridge (Honnorez and Kirst, 1975). Because the overlying sea-floor basalts are not rodingitized, Honnorez and Kirst concluded that the transformation of gabbro-norite dikes into rodingite took place along the shear zones in the lower part of the oceanic crust. Fairly high temperatures and water pressure must have prevailed in this environment.

IMPLICATIONS OF DIFFERENCES IN STRUCTURES OF THE CALAVERAS FORMATION AND THE AMPHIBOLITE

The Calaveras Formation is isoclinally folded and has a well-developed foliation parallel to the axial planes on the crests of the folds and nearly parallel to the bedding along the flanks. The lineation is commonly parallel to the regional fold axes. In places, as near the Dogwood Peak fault, there is a strong second lineation defined by mineral orientation and stretching at right angles to the fold axes (*a* lineation) that indicates the direction of tectonic transport.

The metavolcanic rocks south of Morristown Ravine and those on Reese Ravine seem less deformed than the metasedimentary rocks of the Calaveras Formation. In the metavolcanic rocks, foliation is well developed only in the tuffaceous layers and the lineation is rarely measurable. The parallelism of their foliation with the foliation in the metasedimentary rocks of the Calaveras Formation suggests that all these rocks were deformed together during the Nevadan orogeny. A strong and complicated deformation of the Calaveras Formation indicates that this formation sustained at least two periods of deformation.

Discordance between the structures of the Calaveras Formation and the amphibolite and its metavolcanic border zone is striking. The foliation in the amphibolite and its metavolcanic border zone is parallel to the contact that curves around the circular mass. The lineation in the amphibolite is down the dip, or nearly so, plunging 30° to 70°. In the bordering metavolcanic rocks, it is subparallel to the contact, giving an impression that the structures in these less resistant layers were modified by the regional deformation. This notion is supported by the occurrence of a weak second lineation parallel to the regional trends in the amphibolite and a minor wrinkling around it.

These structural relations indicate that the amphibolite was emplaced after the major phase of the folding of the Calaveras Formation but before the latest phase of the Nevadan deformation. As the amphibolite is 248 m.y. old, which is considered to be Late Permian, the Calaveras Formation must have sustained a strong deformation before that time. The foliation and the orientation of the hornblende prisms parallel to the lineation in the amphibolite must be internal structures resulting from the upward movement of this dome-shaped mass during crystallization from a basaltic magma and subsequent recrystallization. On the other hand, the circular mass has been cut by the Melones fault in the east, proving that the latest movements along this fault zone are younger than 248 m.y. Paleozoic ages of 300 and 387 m.y. reported for hornblende in mafic rocks associated with the Feather River ultramafic body (Standlee, 1978) and the Melones fault near Onion Valley indicate middle Paleozoic tectonic activity along this zone.

CHEMICAL COMPOSITION AND TRACE ELEMENTS OF THE METAVOLCANIC ROCKS AND THE AMPHIBOLITE

The chemical composition of the amphibolite (table 1) is similar to that of metabasalt in the Duffey Dome and Horseshoe Bend Formations except for a higher percentage of iron. The total iron as FeO in the amphibolite is 16 percent, making its composition comparable to Kuno's (1968) high-iron basalts. In the metabasalt of the Horseshoe Bend and Duffey Dome Formations, total iron is 13.2 and 12.3 percent, respectively. These metabasalts and metagabbro sample 2371 have about equal amounts of ionic iron and magnesium, whereas in the amphibolite the ionic percentage of iron is considerably higher than that of magnesium. In contrast most metagabbros in this area have a high magnesium content, the Fe/Mg ratio being about 1:3 (Hietanen, 1973a, table 1). The ionic percentage of calcium in the metabasalt is about equal to that of iron and magnesium as shown by the ternary Ca-Fe-Mg diagram (fig. 7A, plots for anal. 551, 1826); the amphibolite (anal. 2043) has less calcium and more iron, whereas in the meta-andesite of the Franklin Canyon Formation, the percentage of calcium is higher than that of iron and magnesium (fig. 7A, plots for anal. 1589, 2067, 2155, 463).

The purple meta-andesite in the Calaveras Formation on Reese Ravine has an exceptionally high content of ferric iron, bringing the percentage of total iron to 10 percent. In the Ca-Fe-Mg diagram (fig. 7A), this rock (anal. 2237) plots closer to the Fe corner

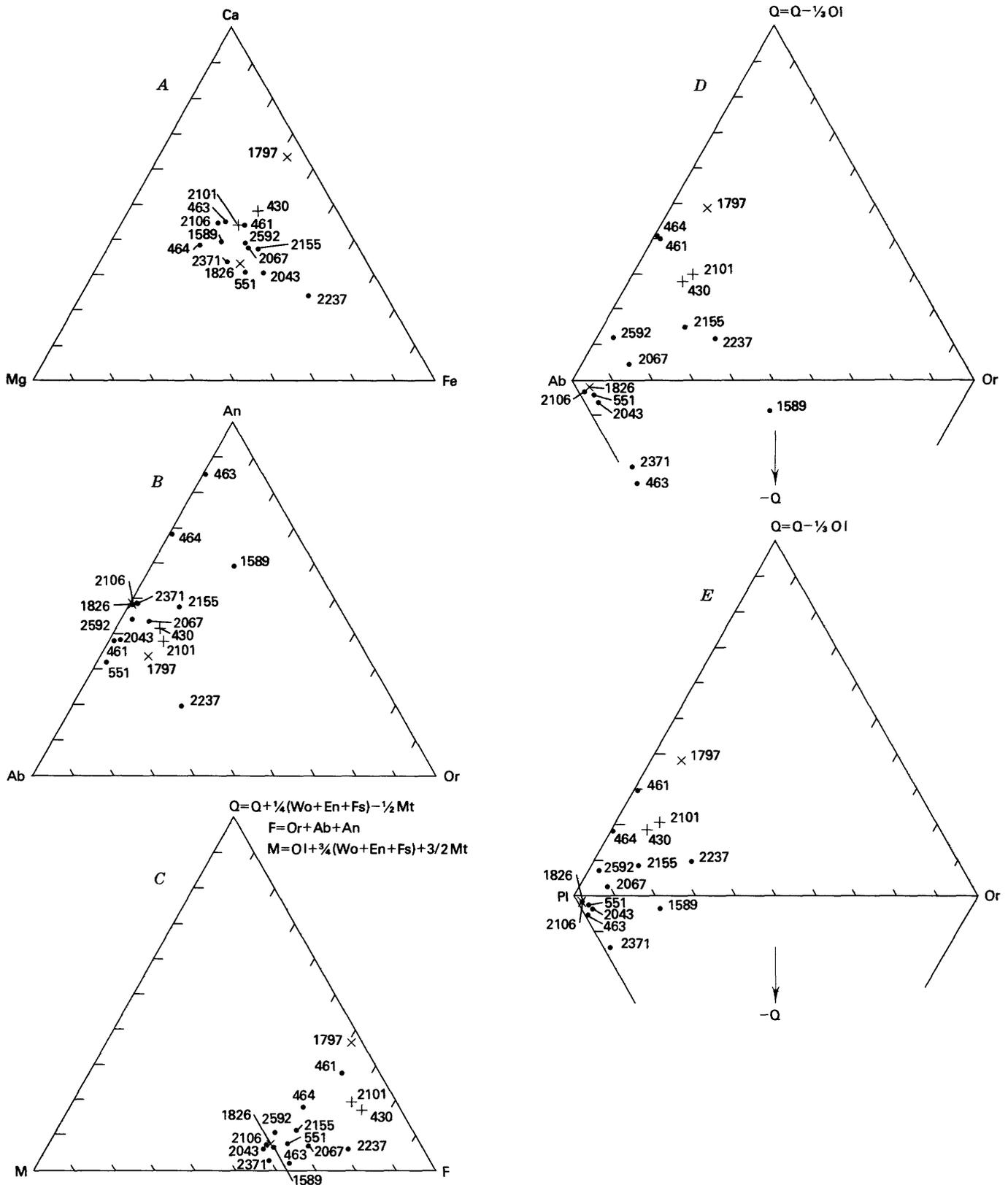


FIGURE 7.—Variation in composition of metavolcanic rocks and amphibolite in molecular percentages. Two analyses of unaltered Tertiary andesites (2101 and 430) and a metagabbro (2371) shown for comparison. Numbers 2371, 2043, 2106, 2592, 1589, 2067, 2155, 2237, and 2101 refer to analyses in table 1; 551, 463, 464, 461 are from Hietanen (1973a, table 1); 1826 and 1797 are metabasalt and metasodaryholite of the Horseshoe Bend Formation (Hietanen, 1977); 430 is from Hietanen (1972). A, Calcium (Ca), magnesium (Mg), and iron (Fe). B, Normative orthoclase (Or), albite (Ab), and anorthite (An). C, Normative quartz (Q), feldspar (F), and mafic minerals as orthosilicates (M). D, Normative quartz minus 1/3 olivine (Q), orthoclase (Or), and albite (Ab). E, Normative quartz minus 1/3 olivine (Q), orthoclase (Or), and plagioclase (Pl).

than the amphibolite (anal. 2043). The sill-like body of amphibolite on the east side of the Melones fault near Claremont (table 1, anal. 2592) is chemically similar to the meta-andesite of the Franklin Canyon Formation and plots close to analysis 2067 in the Ca-Fe-Mg diagram.

In the ternary Or-Ab-An diagram (fig. 7B), the analyses for the amphibolite and for most of the metavolcanic rocks plot near the Ab-An line far from the orthoclase corner. The hematite-rich purple meta-andesite (anal. 2237) on Reese Ravine and the coarse-grained basaltic andesite on Simon Ravine (anal. 1589) have considerably higher percentages of normative orthoclase than the other samples. The purple meta-andesite has a lower content of normative anorthite than any other sample. In contrast, the basaltic meta-andesite (anal. 1589) has a high content of normative anorthite and a high content of mafic minerals which, together with the high content of orthoclase, make the composition of this rock exceptional for the area. The difference in composition is particularly well shown by the Q-Or-Ab diagram (fig. 7D), in which the analysis for the basaltic meta-andesite (anal. 1589) plots halfway between the Ab and Or corners and on the negative Q side, indicating a deficiency in quartz combined with a high orthoclase content. The amphibolite along with the associated metavolcanic rock (anal. 2106) and the metabasalts (anal. 551, 1826) also plot on the negative Q side but near the Ab corner. Owing to a high An content, the basaltic meta-andesite (anal. 1589) plots fairly close to the Pl corner in the Q-Or-Pl diagram (fig. 7E) but still closer to the Or corner than other samples of metavolcanic rocks from the Franklin Canyon Formation. It has been pointed out (Hietanen, 1973a, b; 1975) that the silicic differentiates of the metavolcanic rocks of the Franklin Canyon Formation are very low in potassium, rarely yielding more than 2 percent normative orthoclase. Analyses of two samples from the Bucks Lake quadrangle, 464 and 461, were plotted in diagrams of figure 6 for comparison.

In the Q-F-M diagram (fig. 7C), the amphibolite, metabasalt, and meta-andesite plot close to the F-M line, the amphibolite being richest in mafic constituents and the purple meta-andesite on Reese Ravine (anal. 2237) richest in feldspars. The metasodaryholytes (anal. 1797 and 461) plot close to the Q-F line, indicating a low content of mafic constituents.

The trace-element content of the amphibolite (anal. 2043) differs in many respects from that of the metavolcanic rocks. Amphibolite and the volcanic bomb in the bordering metatuff (anal. 2106) have a relatively high concentration of chromium, stron-

tium, vanadium, yttrium, zinc, and zirconium (table 1) and some barium, cobalt, nickel, scandium, and gallium. The samples of meta-andesite are rich in barium, copper, strontium, vanadium, zinc, and zirconium. They differ mainly from rocks of the other group by their higher concentration of barium, strontium, and copper and lower concentration of chromium and yttrium. The trace-element content of the amphibolite near Claremont (anal. 2592) is similar to that of the amphibolite (anal. 2043) and its border zone (anal. 2106).

Pearce and Cann (1973) and Winchester and Floyd (1976) have pointed out that the concentration of certain minor elements, such as Ti, P, Zr, and Y, does not change during metamorphism. The relations between the concentrations of these elements in the metamorphosed rocks should therefore reflect the possible tectonic setting of the extrusion. The relations between these "immobile" minor elements in the metavolcanic rocks and the amphibolite in the study area are shown in several diagrams (figs. 8, 9, 10).

The plots for two metabasalts in the Zr-Ti diagram are in the field of the ocean-floor basalts if compared with the work by Pearce and Cann (1973). The meta-andesites plot in the field of calc-alkali basalts. The amphibolite (anal. 2043) and the purple metaandesite (anal. 2237) have exceptionally high contents of zirconium and plot outside the fields of other rocks.

In the Zr-P₂O₅ (fig. 8A) and TiO₂-Zr/P₂O₅ (fig. 9) diagrams, the metavolcanic rocks plot in the field designated for the tholeiitic basalts by Winchester and Floyd (1976). The potassium-rich basaltic meta-andesite (sample 1589) has a high P₂O₅ content and plots in the alkaline basalt field in the Zr-P₂O₅ diagram. In the TiO₂-Zr/P₂O₅ diagram, the purple meta-andesite (anal. 2237) plots on the border line of the alkaline basalt field.

The relation between titanium, zirconium, and yttrium is shown in two ternary diagrams (fig. 10A, B) that differ only in the units used for titanium. Using weight percentage for TiO₂ brings the plots to the center of the diagram. Samples from the Jurassic Bloomer Hill Formation plot among those of the Franklin Canyon Formation, which had a similar tectonic setting of extrusion (island arc). Comparison with the results of Pearce and Cann (1973, fig. 3) shows that the metabasalts and meta-andesites plot in the field B or toward the yttrium corner from it. The field B of Pearce and Cann includes ocean floor basalts, calc-alkali basalts, and low-potassium tholeiites. Only the potassium-rich meta-andesites (anal. 1589 and 2237) plot in the field of the calc-alkali basalts (C) in this diagram.

Comparison of the new chemical analyses (table 1) with the analyses previously published (Hietanen, 1973a, 1977) shows that the silica content of the metabasalts, meta-andesites, and their plutonic equivalents in the Feather River area ranges from 46 to 54 percent (fig. 11A). Only the metasodaryholites are rich in silica (from 66 to 74 percent SiO₂). The FeO^{total}/MgO ratio ranges from 1 to 2.6 in the metabasalts and meta-andesites but is less than 1 in common metagabbro, 2.7 in the amphibolite, and 5.3 in hematite-rich meta-

andesite. Titanium (TiO₂) content (fig. 11B) ranges from 0.4 to 1 percent for most metavolcanic rocks and their plutonic equivalents but is very low in metagabbro and exceptionally high (3 percent) in the amphibolite. The metabasalts of the Horseshoe Bend and Duffy Dome Formations have a moderately high TiO₂ content (2 percent). A notable difference in chemical composition between the metabasalts and meta-andesites is the higher calcium content of the meta-andesites, as shown by the Ca-Fe-Mg diagram (fig. 7A). Some of the meta-andesite is exceptionally low in silica, owing to a removal of this element and alkalis during the metamorphism (Hietanen, 1973b). Comparison with the Tertiary andesite (2101, 430) shows a much lower SiO₂ content in the meta-andesites, whereas the TiO₂ content, which is less likely to change during the metamorphism, is about the same magnitude. Change of composition during the metamorphism limits the usefulness of major elements in determining the tectonic environment of extrusion as suggested by Pearce, Gorman, and Birkett (1977).

PLUTONIC ROCKS AND ASSOCIATED DIKES

Two small plutons, one near Scales and the other in Indian Valley, and a stocklike mass have invaded the

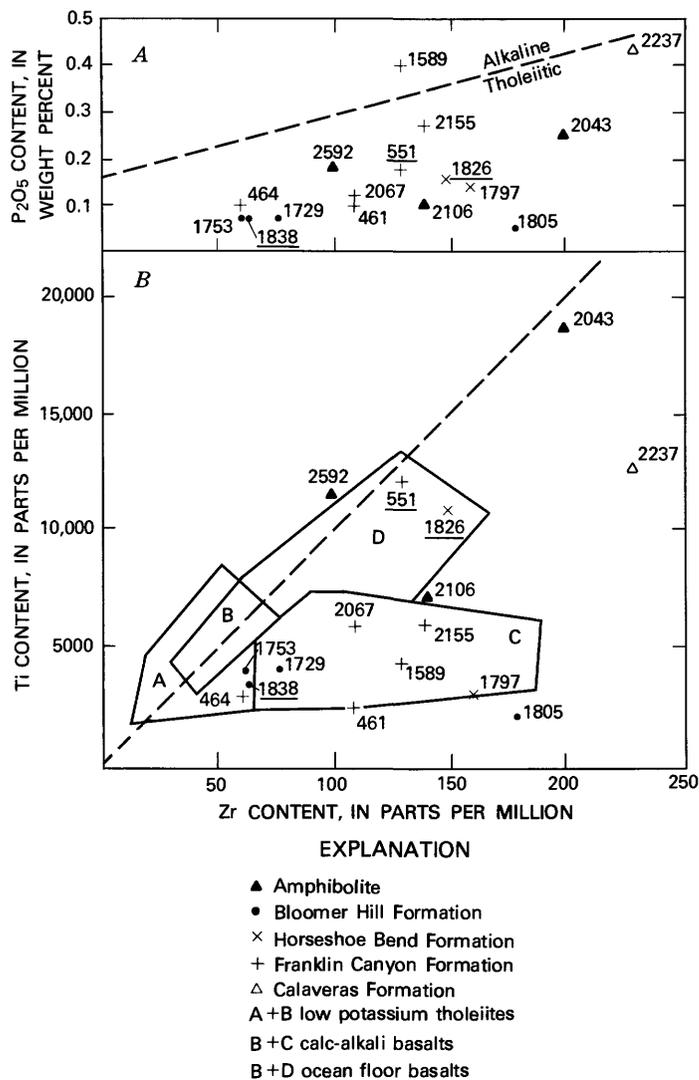


FIGURE 8—Concentration of zirconium (Zr), titanium (Ti), and phosphorus (P) in metavolcanic rocks and amphibolite in Feather River area. Numbers 2043, 2106, 2592, 1589, 2067, 2155, and 2237 refer to analyses in table 1; 551, 464, and 461 from Hietanen (1973a, table 1); 1826, 1838, 1729, 1753, 1805, and 1797 from Hietanen (1977). Numbers representing metabasalts are underlined. A, Zr-P₂O₅ diagram showing line separating tholeiitic and alkaline basalt fields. B, Zr-Ti diagram with an equal distribution line and tectonic subdivision of Pearce and Cann (1973).

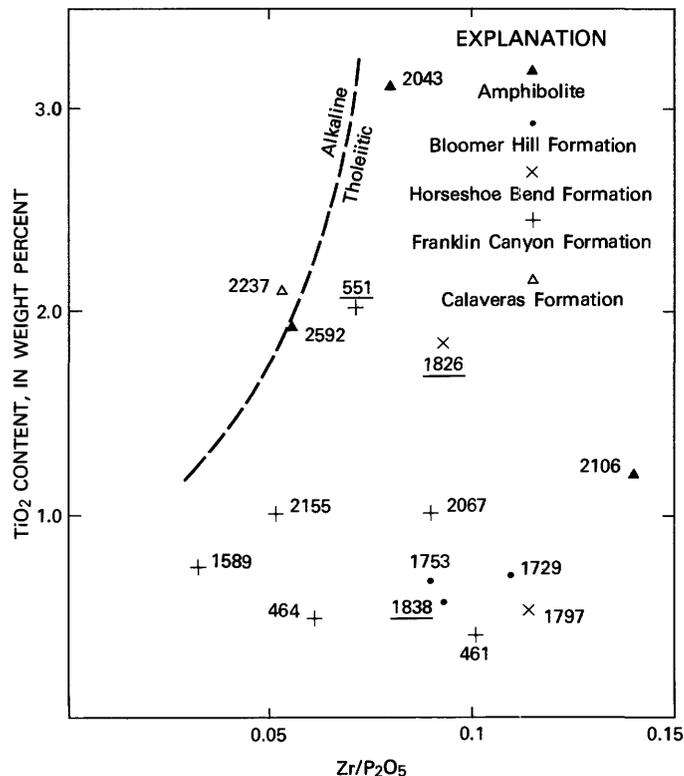


FIGURE 9.—Relation between Zr/P₂O₅ and TiO₂ in metavolcanic rocks and amphibolite. Analyses same as in figure 8.

metamorphic rocks in the western part of the Good-years Bar quadrangle. The Scales pluton is about 8 km² in area. About half of it is hornblende gabbro and gabbroic pegmatite; the other half, mainly in the northeast, is hornblende quartz diorite. Only the northern part of the Indian Valley pluton is in the study area. The major rock type in this pluton is a coarse-grained hornblende quartz diorite that in its texture and mineralogy is similar to the quartz diorite in large plutons farther northwest (Hietanen, 1973a, 1976). A small elongate stock of medium-grained hornblende quartz diorite is exposed 2 to 3 km north of Indian Valley.

A wide southern border zone of the Scales pluton consists of medium-grained hornblende gabbro and gabbroic pegmatite. The potassium-argon age on hornblende in the gabbro (loc. 2458) was determined by J. L. Morton, U.S. Geological Survey, as 160±5m.y. (data: $Ar^{40}_{rad} = 2.383 \times 10^{-10}$ mol/g, 0.989 percent K₂O, 77 percent Ar^{40}_{rad}).

In most of the gabbro, hornblende prisms, which make up 50 to 65 percent of the rock, are parallel to the steeply plunging lineation. Foliation is well developed in the western part of the pluton, less so in the southern part. Thin sections show that much of the plagioclase has altered to epidote, the remaining part being An₂₇. Hornblende is subhedral and pleochroic in bluish green (γ), green (β), and light green (α). Magnetite and sphene occur as accessory minerals. Small aggregates of chlorite transected by relict fractures filled with magnetite probably were originally olivine. They are common in the hornblende-rich southern border zone

and are either included in hornblende or are next to it.

Pegmatitic parts of gabbro consist of large crystals (2 to 10 cm long) of shiny black hornblende and interstitial plagioclase that weathers white. Angular fragments of this coarse-grained rock enclosed in a light-colored hornblende quartz diorite matrix along the southeastern contact of the pluton indicate that the gabbro pegmatite is older than the quartz diorite. Large boulders of this spectacular rock are exposed in the deep gorge of Canyon Creek about 1 km southwest of the mouth of Sawmill Ravine.

The northeastern part of the Scales pluton is hornblende quartz diorite that has 20 to 30 percent hornblende, 55 to 65 percent plagioclase, and about 15 percent quartz. Thin sections show that hornblende and plagioclase occur as large (2 to 3 mm long) subhedral crystals and that small anhedral grains of quartz fill the interstices. The centers of plagioclase (An₂₇) crystals include numerous small grains of epidote and muscovite. In gabbroic quartz diorite, some augite is included in centers of large hornblende crystals. A part of epidote occurs as fairly large crystals, some of them clustered with chlorite or included in hornblende. Biotite in this rock is altered to light-green chlorite that includes colorless lamellae of muscovite and small elongate grains of rutile and leucoxene along the cleavage. Magnetite, apatite, allanite, and sphene occur as accessory minerals. Most of the magnetite is included in hornblende. A myrmekite-like intergrowth of magnetite and hornblende occurs in the centers of some hornblende crystals.

The elongate hornblende quartz diorite stock west of

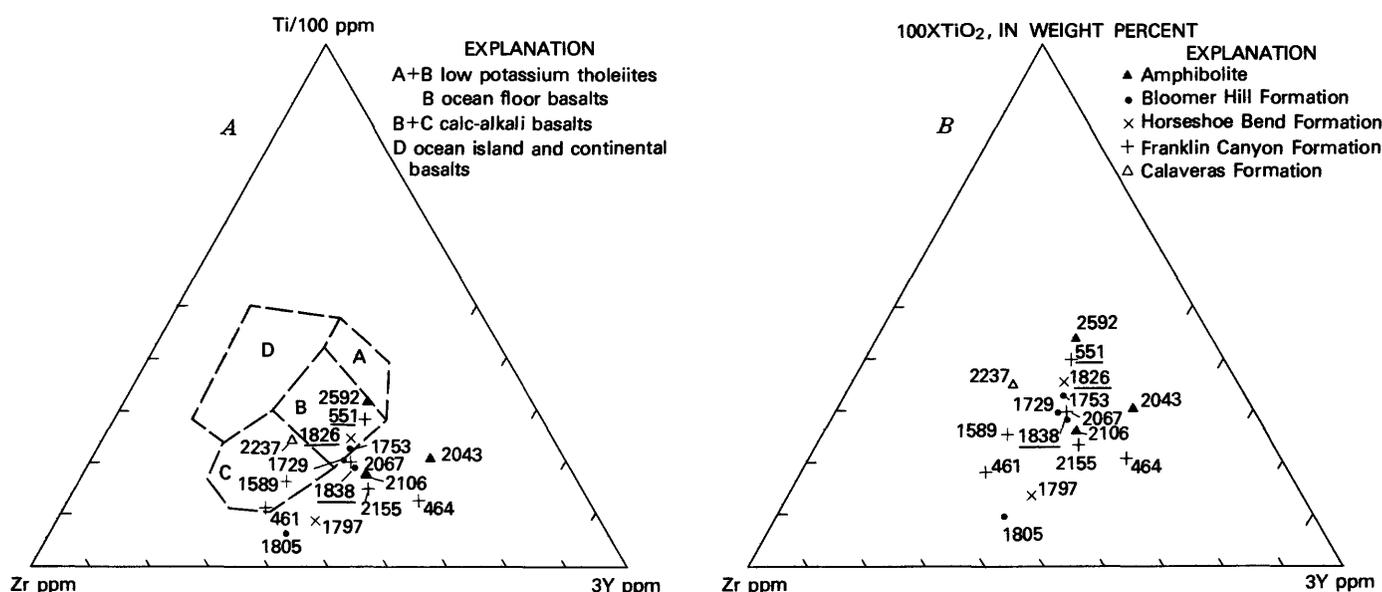


FIGURE 10—Relative contents of zirconium (Zr), yttrium (Y), and titanium (Ti) in metavolcanic rocks and amphibolite of Feather River area. Analyses same as in figure 8. A, Titanium in parts per million (ppm). B, TiO₂ in weight percent.

Halls Ranch consists of plagioclase (An_{32-34}), quartz, hornblende, some biotite, epidote, and magnetite. Plagioclase is in euhedral to subhedral crystals that include the alteration products epidote and muscovite. Early crystals are zoned; their centers consist mainly of epidote minerals. Subhedral 1-to 3-mm-long hornblende prisms in a random arrangement are pleochroic in bluish green (γ), green (β), and light green (α). Biotite is included in or is next to the hornblende. Some of the epidote is clustered with the dark minerals. Quartz is interstitial.

The brownish-gray or greenish-gray color, strong lineation, grain size, and alteration of major constituents of this quartz diorite are features similar to those of small quartz dioritic stocks and the Lumpkin pluton in the Clipper Mills quadrangle (Hietanen, 1976). All of these bodies, as well as the Scales pluton, are more altered and more strongly deformed than the large Cretaceous plutons west of the study area (Hietanen, 1973a, 1976). The 160-m.y. age of the Scales pluton confirms the Jurassic age of this earliest group of plutonic rocks in the Feather River area.

The Indian Valley pluton consists of coarse-grained tonalite and hornblende-biotite quartz diorite in which dark constituents make up 15 to 18 percent of the rock,

plagioclase 55 to 60, and quartz about 20. Potassium feldspar content is low (0 to 5 percent). Plagioclase is in large (2 to 5 mm long) subhedral zoned and complexly twinned crystals that include the alteration products epidote and muscovite. Hornblende prisms are subhedral to anhedral and 1 to 4 mm long. A few are partly altered to chlorite that includes epidote. About 25 percent of the dark minerals is biotite that occurs as large scattered flakes, some partly altered to chlorite. Magnetite, ilmenite, sphene, apatite, and occasionally calcite occur as accessory minerals. Large grains of sphene show twinning lamellae; small grains are clustered with hornblende and biotite.

Dikes of porphyritic hornblende quartz diorite cut the contact-metamorphosed aureoles of the Indian Valley pluton on its east side. Phenocrysts of plagioclase make up about 60 percent of these dikes; the groundmass is medium grained, consisting of small grains of plagioclase, quartz, biotite, hornblende, and a few small grains of potassium feldspar and myrmekite. The accessory minerals are magnetite, apatite, sphene, and zircon. Plagioclase phenocrysts are euhedral, strongly zoned, and complexly twinned. The centers of some crystals are studded with the alteration products epidote and muscovite.

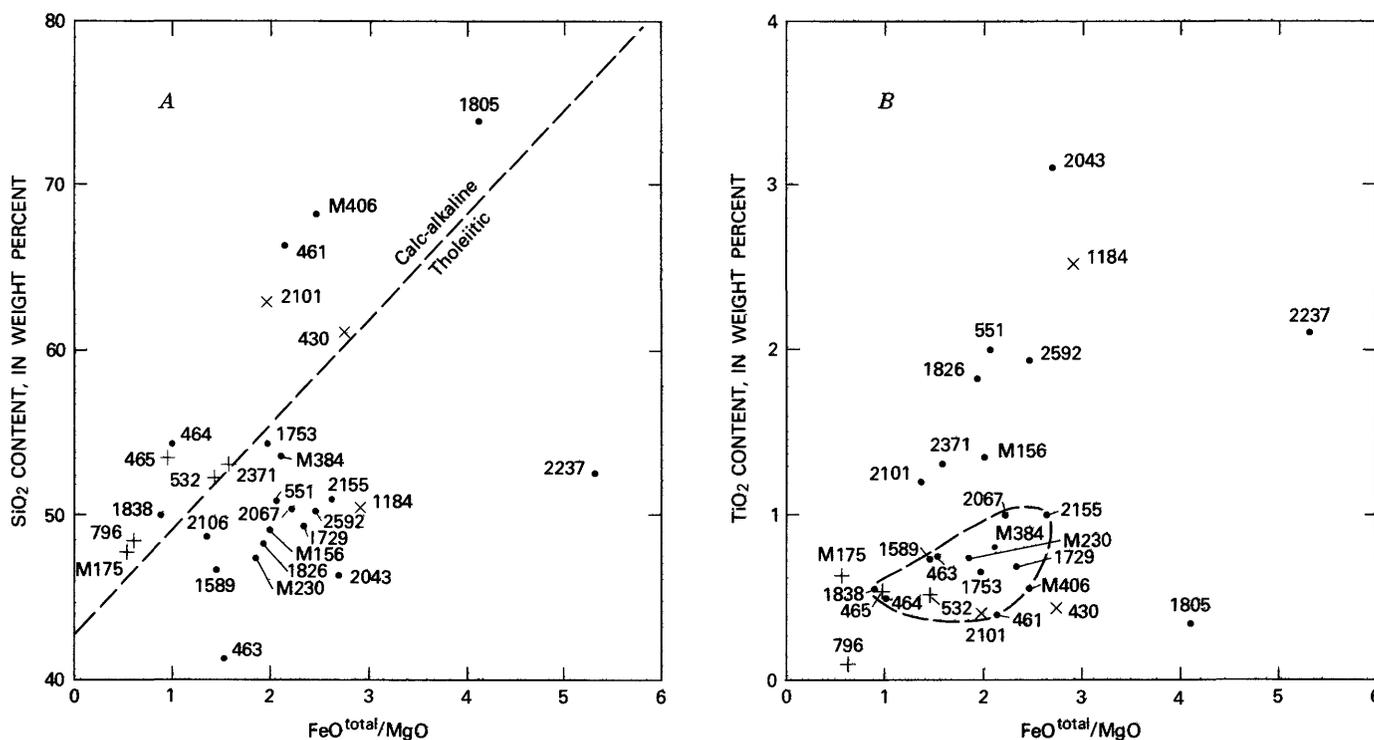


FIGURE 11.—Variation of SiO_2 (A) and TiO_2 (B) with increasing FeO^{total}/MgO ratio in metavolcanic rocks and their plutonic equivalents (+) in Feather River area. Two analyses of unaltered Tertiary andesite (Nos. 430 and 2101) and one of Lovejoy Basalt (No. 1184) were added for comparison. Numbers 2371, 2043, 2592, 1589, 2067, 2155, 2237, and 2101 refer to analyses in table 1; 1826, 1838, 1729, 1753, and 1805 from Hietanen (1977); 796, 532, 465, 551, 463, 464, and 461 from Hietanen (1973a, table 1); numbers with prefix M from Hietanen (1951).

Porphyritic dikes ranging in composition from trondhjemitic to tonalitic and quartz dioritic are common in the southwestern part of the area. Several such dikes cut the phyllite along the east branch of Cherokee Creek, 2 km northwest of Halls Ranch. The quartz dioritic and tonalitic dikes have phenocrysts of plagioclase and hornblende in a medium-grained groundmass consisting mainly of plagioclase, quartz, hornblende, chlorite or biotite, and magnetite.

A trondhjemitic dike at locality 2383 has about 50 percent plagioclase, 40 percent quartz, some biotite, and calcite. Plagioclase grains are subhedral to euhedral and larger than the other mineral grains. The centers of most plagioclase crystals include alteration products, epidote and sericite. Quartz shows strain shadows and has interlocking boundaries. Biotite is partly altered to chlorite.

Quartz porphyry dikes at localities 2361 and 2380 are trondhjemitic in composition. Phenocrysts are quartz and plagioclase (An_{12}), and the groundmass consists of quartz, plagioclase, hornblende, chlorite, muscovite, and some magnetite. At locality 2361, hornblende is altered to chlorite and epidote. Radiating bundles of reddish-brown stilpnomelane occur at locality 2380, just southwest of the Ramshorn fault zone.

Plagioclase (An_{20}) occurs as large (1 to 2 mm long) subhedral phenocrysts in a trondhjemitic dike south of Gibsonville (loc. 2074). The groundmass of this dike is medium grained and consists mainly of quartz, plagioclase, hornblende, chlorite, muscovite, epidote, and some magnetite and apatite. Hornblende is pale green and partly altered to chlorite and epidote. Small clusters of muscovite and zoisite are scattered through the groundmass and occur as inclusions in the plagioclase phenocrysts.

AURIFEROUS STREAM DEPOSITS

Auriferous Eocene gravels are widespread in the study area, particularly in the La Porte quadrangle. They were until recent years extensively mined for gold by hydraulicking and drifting, but at the present, only a few mines are active, most of them working in a small way.

The auriferous deposits in this area are white quartz gravels and sands derived from gold-bearing quartz veins that transected the pre-Cretaceous metamorphic rocks. The gravel deposits line up parallel to Eocene river channels and are now exposed on ridges and partly covered by Tertiary volcanic rocks. Turner (1897), Lindgren (1911), and Haley (1923) give a detailed account of these old river channels. Much of their data is based on miners' records from tunnels driven under the Tertiary volcanic rocks. According

to Turner (1897), the Eocene drainage system had two major forks that joined just north of Scales in the Goodyears Bar quadrangle.

The north fork of this Eocene river channel is parallel to Slate Creek on its northwest side. Most of the gravels in this channel are now covered by pyroclastic andesite of Gibsonville Ridge. This channel has been mined at Poverty Hill in the northeast corner of the Strawberry Valley quadrangle; at Barnard Diggings, Secret Diggings, La Porte, Thistle Shaft, and Gibsonville in the La Porte quadrangle; and at Whiskey Diggings in the Onion Valley quadrangle. Eocene gravels at the headwaters of Onion Valley Creek and those under the Little Grass Valley Lake may have been deposited by a northern branch of this fork.

Lindgren (1911) reports interruptions in the elevation of lowest gravel beds in the channel between La Porte and the vicinity east of Gibsonville. The gravel beds have moved down on the northeast side as a result of faulting in the underlying bedrock. These post-Eocene faults are along or near the Dogwood Peak and Melones fault zones, but the movement recorded in the gravel beds is opposite the movement that occurred along these fault zones during late Paleozoic and Jurassic time. Lindgren (1911) also reports an unrealistically high grade of 200 feet per mile (25 m per km) between La Porte and the northeast corner of the La Porte quadrangle and suggests that the block between the two fault zones was tilted sharply westward (about 20 m per km).

The south fork of the Eocene river channel is on the southeast side of Slate Creek on Port Wine Ridge. The gravels of this channel are exposed north of the pyroclastic andesite at the Lucky Hill mine, Port Wine, Queen City, Grass Flat, St. Louis, Howland Flat, and Potosi. From there on the channel continues under the pyroclastic andesite ridge to Poker Flat, 3.5 km southeast in the Mount Fillmore quadrangle. Interruptions in elevation of the lowest gravel beds in mining tunnels driven into this channel indicate similar faulting of the bedrock under the pyroclastic andesite as found along the north fork channel.

A southeastern branch of the Port Wine channel extended to Howland Flat from Deadwood Diggings and the California mine in the Mount Fillmore quadrangle. An andesite wall under Table Rock now separates these gravels from those on Howland Flat.

At the time Turner (1897) worked in this area, not all gravels near Howland Flat had been hydraulicked, and the upper surface of the gravel beds was exposed. The irregularity of this surface indicated that the gravel beds had been considerably eroded before they were covered by the Tertiary pyroclastic andesite.

The channel that deposited white quartz gravels on Morristown Ridge and at Eureka Diggings may have been a southern branch of the Port Wine channel (Turner, 1897; Lindgren, 1911), or this branch may have drained southeastward into the White Bear channel, which extends from Saddleback Mountain through White Bear and Monte Cristo mining sites to Goodyears Creek (Haley, 1923).

The La Porte area is one of the richest placer mining areas in California. Most of the gold has been found on top of bedrock and fairly evenly distributed in the lowest 60 cm of gravel. Much of unexplored gravel still remains under the Tertiary volcanic rocks and should be good ground for future drifting.

Gravel beds on the southeast side of Canyon Creek in the Goodyears Bar quadrangle contain pebbles of dark quartzite, siliceous schist, and Tertiary lavas. These gravels are exposed in Bunker Hill, Sailor Boy, and McMahan mines at the edge of pyroclastic andesite and are probably part of a southward-draining subordinate intervolcanic channel.

TERTIARY VOLCANIC ROCKS

Tertiary volcanic rocks in the study area are continuous with those in the neighboring Bucks Lake and American House quadrangles (Hietanen, 1973a, 1976). The Lovejoy Basalt, of Miocene age (Dalrymple, 1964), is exposed between the 5,000- and 6,200-foot altitudes in the Onion Valley quadrangle and around Little Grass Valley Reservoir. Pyroclastic andesite that is probably correlative with the Pliocene Penman Formation of Durrell (1959b, 1966) covers the highest parts of most ridges. The olivine basalt and its silicic derivative, the platy andesite, are on hilltops above the pyroclastic andesite and by their position are the youngest extrusive rocks in the area.

LOVEJOY BASALT

The Lovejoy Basalt on the south side of the Little Grass Valley Reservoir is similar to the Lovejoy Basalt described from the west side of the lake (Hietanen, 1972). Large scattered phenocrysts of labradorite (An_{60}), some of them clustered, are common on the east side. A few scattered large magnetite crystals along with plagioclase are embedded in a fine-grained groundmass consisting of small laths of plagioclase, tiny subhedral grains of augite and magnetite, and interstitial glass.

In the Onion Valley quadrangle, three to four flows are exposed on the slopes of the Onion Valley Creek and on the headwaters of Washington Creek. The uppermost flow north of Chimney Rock has numerous large white plagioclase phenocrysts in an aphanitic groundmass. Thin sections show that these

phenocrysts are clusters of several large labradorite laths with complex twinning. The groundmass is glassy and includes tiny grains of magnetite, small laths of plagioclase, and a few small grains of olivine and augite.

PYROCLASTIC ANDESITE

Pyroclastic andesite covers most of the highest parts of long ridges that traverse the study area in a northeasterly direction. In the southwestern and western parts, the contact with the underlying rock is close to the 4,400- to 5,000-foot contours but rises to the 5,600- to 5,800-foot contours toward the northeast. In the easternmost part, the contacts are more irregular and the pyroclastic rocks cover deep canyons in some places. Most of the pyroclastic material on ridges consists of well-rounded boulders a few centimeters to about a meter in diameter and of gray sandy soil. Mudflow breccia containing round to subangular fragments of porphyritic andesite in a fine-grained matrix is exposed in many road cuts. Most of the boulders and large fragments consist of light- to medium-gray porphyritic andesite containing numerous euhedral to subhedral plagioclase phenocrysts in a fine- to medium-grained groundmass. Small black hornblende and augite phenocrysts are generally scattered, but in places large (2 to 10 mm long) phenocrysts constitute as much as 20 percent of the rock.

Thin sections show that the plagioclase phenocrysts constitute as much as 50 percent of the light-gray andesite but only 10 to 40 percent of the darker rock. In many boulders, there are two generations of plagioclase phenocrysts, large ones 2 to 3 mm long and small ones 0.5 mm long. All phenocrysts are weakly zoned and complexly twinned. Dusty inclusions either in the center or in certain zones of plagioclase phenocrysts are common. Augite phenocrysts are subhedral and smaller (0.5 to 2 mm long) than the plagioclase phenocrysts. Scattered hornblende phenocrysts, most of them rimmed with magnetite or altered to magnetite and pyroxene, are common and in places constitute 5 to 10 percent of the rock.

Hornblende phenocrysts are unaltered only in the andesite that has few but large phenocrysts of plagioclase and hornblende in a groundmass that is mainly glass. The lava was obviously brought up and cooled quickly, and the hornblende remained unaltered. In the common hornblende porphyritic rock, every degree of alteration of hornblende to magnetite is seen in thin sections. In most thin sections, brown hornblende has a rim of magnetite, 0.01 to 0.5 mm thick. At the advanced state of alteration, the former

hornblende crystals can be identified by the shape of the fine-grained magnetite aggregates, which may or may not have some hornblende in their centers. The groundmass in all types of andesite consists of tiny subhedral crystals of augite, plagioclase, magnetite, and interstitial glass.

Andesite in the easternmost part of the area, on Saddleback Mountain and vicinity, is light to medium gray and has small phenocrysts of plagioclase (An_{45}) and hornblende. Thin sections show that there are two generations of plagioclase phenocrysts. The larger ones are 0.2 to 1 mm long and have a zone clouded by dustlike inclusions close to the rim. The clouded zone has rounded corners, but the rim, free of inclusions, has well-defined crystal faces and sharp edges. The small plagioclase phenocrysts are 0.05 to 0.15 mm long and clear. The hornblende phenocrysts are 1 to 3 mm long and have thick rims of fine-grained magnetite. The inclusion-free centers are pleochroic in brown and light brown. The groundmass consists of tiny laths of plagioclase, small grains of augite and magnetite, and interstitial glass. The laths of plagioclase are in either a random or subparallel arrangement.

A small pluglike body east of Oak Ranch consists of gray fine-grained andesite with small plagioclase and scattered augite and hornblende phenocrysts. Thin sections show that hornblende is altered to magnetite to the extent that only a little, if any, occurs in the centers of large magnetite aggregates. In the main pyroclastic andesite mass to the east, south of Fir Cap, phenocrysts and clusters of augite are common, and the magnetite aggregates after hornblende include small grains of augite.

Farther north, south of Democrat Peak, the plagioclase phenocrysts are well rounded and only some have dusty rims. Much of the andesite in this vicinity contains two generations of magnetite aggregates after hornblende, the smaller ones being in the groundmass. Some brown hornblende was preserved in the centers of large phenocrysts. These relations indicate that hornblende crystallized early in the andesite magma but became unstable during the ascent of the magma, leaving only skeletons consisting of fine-grained magnetite. Augite was the stable dark constituent at the eruptive stage.

OLIVINE BASALT AND PLATY ANDESITE

Several cone-shaped or pluglike bodies of medium- to dark-gray olivine basalt and related light-gray platy andesite are exposed either above the pyroclastic andesite or on hilltops elsewhere. These rocks are mineralogically similar to the gray olivine basalt and two-pyroxene andesite in the Bucks Lake and

American House quadrangles (Hietanen, 1972).

The largest exposure of olivine basalt is at Deadwood Peak on the border of the La Porte and Mount Fillmore quadrangles. In this rock, dark-green olivine crystals are embedded in a light-gray medium-grained groundmass consisting of augite, olivine, plagioclase, magnetite, and ilmenite. The olivine phenocrysts are 1 to 2 mm long and rimmed by tiny magnetite grains. Plagioclase is in small laths (0.5 mm long) subparallel to the flow structure. These laths and small stubby augite crystals are clouded by tiny grains of magnetite and ilmenite. In many small bodies such as those on the Morrystown Ridge and near Gibsonville, plagioclase laths are about 1 mm long and well oriented parallel to the flow structure. Magnetite in these rocks occurs as a few medium-size grains suggestive of a more complete crystallization. The border zones of small cones are fine grained and have small phenocrysts. Augite along with olivine occurs as phenocrysts on Morrystown Ridge west of Deadwood Peak.

Similarity in the mineralogy of the olivine basalt in these occurrences and olivine basalt described from the Bucks Lake and American House quadrangles (Hietanen, 1972, table 1) suggests a similarity in chemical composition. In the Bucks Lake quadrangle, a two-pyroxene andesite on Mount Ararat has a composition intermediate between the olivine basalt at Camel Peak and platy andesite on Table Mountain. In the La Porte and Mount Fillmore quadrangles, the olivine-bearing andesite on Table Rock and to the east, north of Skyhigh, represents a similar intermediate member between the olivine basalt and the platy andesite.

The olivine-bearing andesite is well exposed on the two highest peaks of Table Rock at the border of the La Porte and Mount Fillmore quadrangles. This rock is medium gray and fine grained and contains scattered small phenocrysts of augite, olivine, and plagioclase. The elongation of phenocrysts is parallel to a well-developed flow structure. Thin sections show that augite and olivine phenocrysts are clustered. Olivine occurs in small (0.5 to 1 mm long) subhedral crystals with some olivine-green antigorite along the cracks and borders. Augite crystals of the same size but more numerous are next to, or around, the olivine crystals. Plagioclase (An_{45-55}) phenocrysts are subhedral with well-rounded corners and clear centers. The rims are clouded by tiny inclusions of iron oxide and some small clusters of tiny grains of augite. Pseudomorphs consisting of small grains of augite and magnetite, many with external shapes of hornblende crystals, are scattered and were originally hornblende. Some of these large altered horn-

blende phenocrysts include medium-size plagioclase crystals. The groundmass consists of 0.1- to 0.2-mm-long laths of plagioclase and prisms of clino- and ortho-pyroxene and tiny crystals of magnetite. The small laths of plagioclase and prisms of pyroxene are parallel to the flow structure and encircle the phenocrysts of olivine, augite, and plagioclase.

Most occurrences of platy andesite reveal more plagioclase and fewer dark minerals than the olivine-bearing andesite at Table Rock. The most silicic variety is light gray and fine grained and has a closely spaced subhorizontal parting. Thin sections show that plagioclase laths (0.3 to 1 mm long) of the groundmass are parallel to the parting, which thus developed parallel to the flowage of the magma. The pyroxene phenocrysts are few and small, and olivine is rare. The platy andesite on La Porte Mountain and the fine-grained andesite on Democrat Peak contain scattered aggregates of magnetite + augite with outlines of hornblende and small phenocrysts of plagioclase. These rocks contain about 60 percent plagioclase, whereas the rock at Goat Mountain and at Little Table Rock contain 70 to 75 percent plagioclase, all in the groundmass. The very light gray variety occurs on Bald Mountain and on a hill to the south in the Goodyears Bar quadrangle.

An exceptionally mafic fine-grained two-pyroxene andesite is exposed at the junction to Saddleback Lookout. This rock contains about 50 percent ortho-

pyroxene and clinopyroxene, 48 percent plagioclase (An_{32-40}), and some magnetite. The small laths of plagioclase and prisms of pyroxenes are well orientated parallel to the flow structure. Tiny subhedral grains of magnetite are evenly scattered throughout the rock.

Chemical composition of the plagioclase-rich andesite at Goat Mountain (table 1, anal. 2101) is similar to that of the platy andesite at Table Mountain in the Bucks Lake quadrangle (Hietanen, 1972, table 1 anal. 430) except for a somewhat higher content of silica and lower content of aluminum and calcium. In the ternary diagrams (fig. 7), analysis 2101 plots closer to the quartz corner than analysis 430 and thus represents the silicic end member of the olivine basalt—two-pyroxene andesite differentiation series in the area.

CONCLUSIONS

The Melones fault separates the continentally derived quartzite and schist of the Silurian Shoo Fly Formation on the east from the oceanic metachert and phyllite of the Pennsylvanian Calaveras Formation on the west. The metavolcanic rocks interbedded with the metasedimentary rocks of the Calaveras Formation consists of metabasalt, metaandesite, metadacite, metasodarhyolite, and meta-tuff that are mineralogically similar to the metavolcanic rocks of the Franklin Canyon Formation.

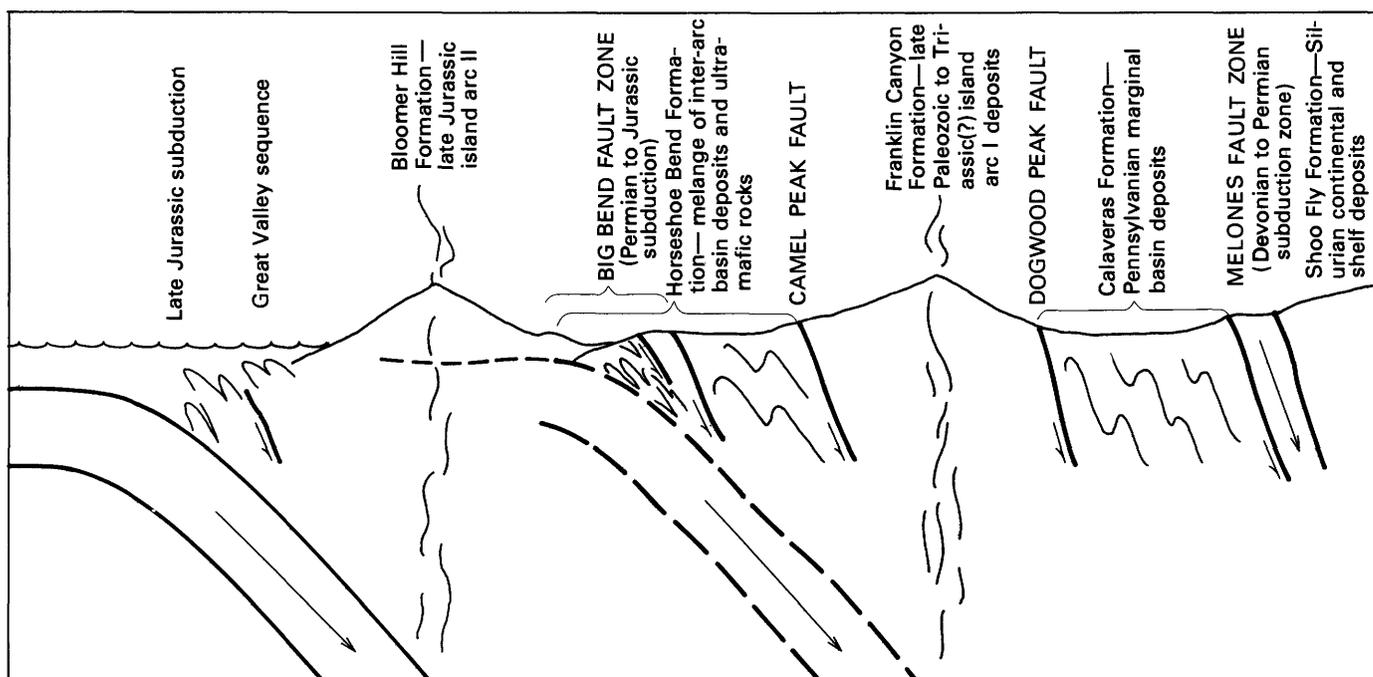


FIGURE 12.—Possible tectonic environment of deposition of metasedimentary and metavolcanic rock units between the Great Valley sequence and the Shoo Fly Formation.

The deposition of the Calaveras Formation in the marginal sea was probably coeval with the volcanism in the island arc (the Franklin Canyon Formation), both taking place in late Paleozoic time. The volcanism may have continued to Triassic time in the southern part of the study area, where Triassic metasedimentary rocks containing well-preserved radiolarians overlie, and may also be interbedded with the less-deformed and less-metamorphosed southwestern part of the Franklin Canyon Formation.

New chemical and spectrographic analyses (table 1) together with the analyses published previously (Hietanen, 1973a) confirm the earlier finding that metavolcanic rocks of the Franklin Canyon Formation have chemical characteristics and a trace element content of early island-arc tholeiites and andesites. The subduction that gave rise to the island-arc volcanism was probably along the Big Bend fault zone, which now separates the interbedded metavolcanic and metasedimentary rocks of the Permian(?) Horseshoe Bend Formation (Hietanen, 1976, 1977) on the west side of the island arc from the Jurassic metavolcanic rocks farther west (fig. 12).

The metamorphic rocks within the Melones fault zone west of Downieville are highly contorted and intricately folded, exhibiting tectonic styles typical of trench melanges. The enclosed layers and lenses of metabasalt contain crossite, lawsonite, pumpellyite, and stilpnomelane in addition to typical greenschist facies minerals: chlorite, albite, and epidote. The occurrence of these minerals indicates low temperatures and medium pressures during the metamorphism, physical conditions typical of subduction zones. Devonian (Standlee, 1978) to Pennsylvanian and Permian ages (this paper) for the metagabbro and amphibolite within the next to the Melones fault zone suggest Paleozoic time for the subduction. Movement along these early subduction zones and along many faults developed parallel to them were renewed during Jurassic time, the time of major deformation and beginning of plutonism in the site of early island-arc volcanism.

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The Feather River Area as a Part of the Sierra Nevada Suture System in California

By ANNA HIETANEN

PETROLOGIC AND STRUCTURAL STUDIES IN THE NORTHWESTERN SIERRA NEVADA

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1226-B

*Plate-tectonic implications of the major fault zones
and various metamorphic rock units in the area*



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PETROLOGIC AND STRUCTURAL STUDIES IN THE NORTHWESTERN SIERRA NEVADA

THE FEATHER RIVER AREA AS A PART OF THE SIERRA NEVADA SUTURE SYSTEM IN CALIFORNIA

By ANNA HIETANEN

ABSTRACT

The three major metamorphic rock units of the Feather River area, from east to west, are: (1) the Silurian Shoo Fly Formation, consisting of continentally derived shelf sediments; (2) late Paleozoic and Triassic metasedimentary and metavolcanic rocks, and (3) Jurassic island-arc-type metavolcanic rocks. The late Paleozoic and Triassic rocks, which are exposed between two major sutures, the Melones and Big Bend faults, consist of three subunits that from east to west are: (a) interbedded metachert and phyllite of Pennsylvanian age, deposited with minor metavolcanic rocks into a marginal basin; (b) an island-arc-type metavolcanic series of late Paleozoic age, and probably as young as Triassic in the southern part of the area; and (c) interbedded metasedimentary and metavolcanic rocks, deposited on the ocean side of the island arc and now forming an imbricated melange with sheetlike bodies of ultramafic rocks. Pieces of oceanic lithosphere on which the island arc was built are preserved in the southern part of the area.

An imbricated melange along the Big Bend fault zone and the presence of high-pressure/low-temperature minerals along the Melones fault indicate that these two sutures are the surface expressions of two subduction zones that farther south (at lat 38°30' N.) join to form a major structural zone containing melange between the Melones and Bear Mountains faults. The southernmost exposures of this system of sutures are the ultramafic rocks along the west edge of the Sierra Nevada batholith, between the 36th and 37th parallels.

Northwest of the study area the zone of melange is covered by Cretaceous sedimentary rocks of the Great Valley sequence and Cenozoic volcanic rocks, but the zone is exposed again in the Klamath Mountains, where it separates Late Jurassic rocks on the west from late Paleozoic and Mesozoic rocks on the east. Farther east the Trinity thrust separates late Paleozoic and Triassic rocks from older Paleozoic rocks on the east. Thus the Trinity thrust occupies the same structural position as the Melones fault, although its age is early Paleozoic, whereas the Melones fault in the Feather River area was active from Devonian to Permian time, and farther south it was active into the Jurassic. In the Feather River area, Mesozoic subduction was along the Big Bend fault zone, and Late Jurassic island-arc-type volcanism west of this zone was a result of the Benioff zone stepping farther westward to the Coast Ranges.

The width of the suture system in the Sierra Nevada foothills south of lat 38°30' N. is 7 km; to the north it widens to 40 km at the 40th parallel and to 55 km in the Klamath Mountains. Its total length from the Garlock fault in southern California to the Klamath province in Oregon is about 1000 km. The suture system was formed along the continental margin as a result of subduction of the Pacific plate under the North American plate from early Paleozoic to early Mesozoic time.

INTRODUCTION

This report is based on work done during 1964-78 in the northwestern Sierra Nevada (Hietanen, 1973a, 1976, 1977, 1980) and provides a regional setting for tectonic events in an important part of the western Cordillera during late Paleozoic and Mesozoic time.

The report contains a short summary of lithologic, petrologic, and structural features of the Paleozoic rocks west of the Melones fault between the North Fork of the Feather River and the North Yuba River (fig. 1) and provides a basis for correlation of the geologic units within the northwestern metamorphic belt of the Sierra Nevada and the Klamath Mountains necessary for interpretation of tectonic events. Late Paleozoic rocks and some early Mesozoic rocks are exposed between two major sutures considered to represent northern branches of a major subduction zone that at lat 38°30' N. is bordered on the east by the Melones fault and on the west by the Bear Mountains fault. The older northeastern branch is known as the Melones fault zone (fig. 2), and the younger southwestern branch is called the Big Bend fault zone. A wide zone of melange on the northeast side of the Big Bend fault is bordered on the northeast by the Camel Peak fault (pl. 1). It is probably the southern extension of this fault that on the "Geologic map of California, Sacramento sheet" (Strand and Koenig, 1965) is shown to join the Melones fault at lat 38°45' N. Farther south, only a narrow zone of melange and some metavolcanic rocks are present between the Bear Mountains and Melones faults (Duffield and Sharp, 1975).

The study area, which lies northeast of Lake Oroville (fig. 1), comprises about 2500 km² at the north end of the western metamorphic belt of the Sierra Nevada. The geologic map (pl. 1), showing the major pre-Tertiary geologic features in this area, is compiled from the geologic maps of the Pulga and Bucks Lake 15-minute quadrangles (Hietanen, 1973a), the Brush Creek, Cascade, American House, Clipper Mills, and Strawberry Valley 7½-minute

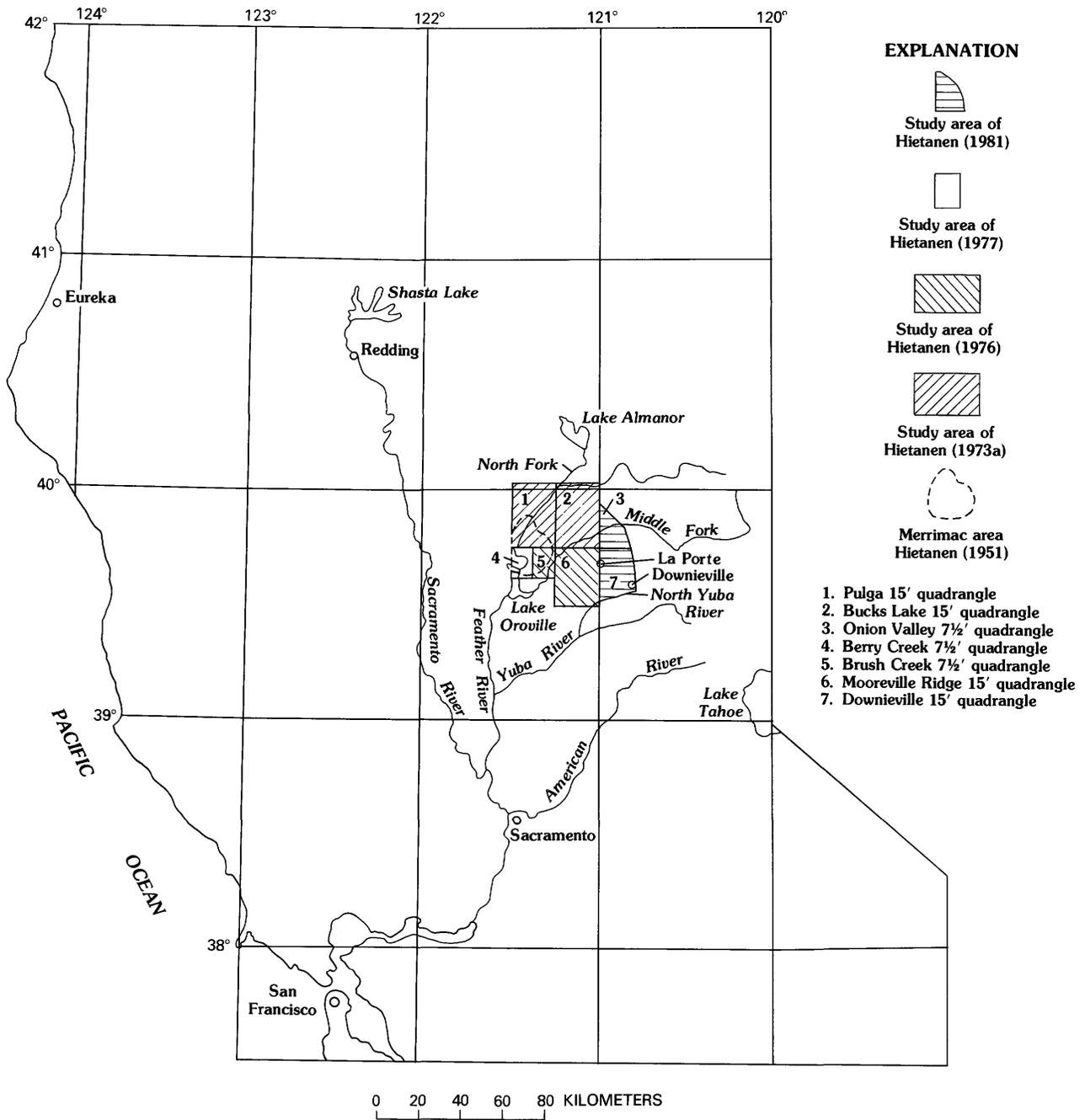


FIGURE 1.—Index map of study area in northern California.

quadrangles (Hietanen, 1976), the Berry Creek 7½-minute quadrangle (Hietanen, 1977), and the Onion Valley, La Porte, and Goodyears Bar 7½-minute quadrangles and vicinity (Hietanen, 1980).

In this area the northerly trends of the western metamorphic belt of the Sierra Nevada turn northwesterly toward the Klamath Mountains. The continuity, however, is interrupted by a cover of Cenozoic volcanic rocks and the Great Valley sequence, and so correlation must be based on lithology and age of the rock units.

MAJOR GEOLOGIC FEATURES

The three major metamorphic rock units in the study area (pl. 1), from east to west, are: (1) the Shoo Fly Formation of Silurian age, (2) late Paleozoic and Triassic metasedimentary and metavolcanic rocks, and (3) Jurassic metavolcanic rocks. The Shoo Fly Formation consists of continentally derived blastoclastic quartzite and mica schist containing minor layers of metachert and carbonate rocks. These Silurian rocks are separated by a major suture, the

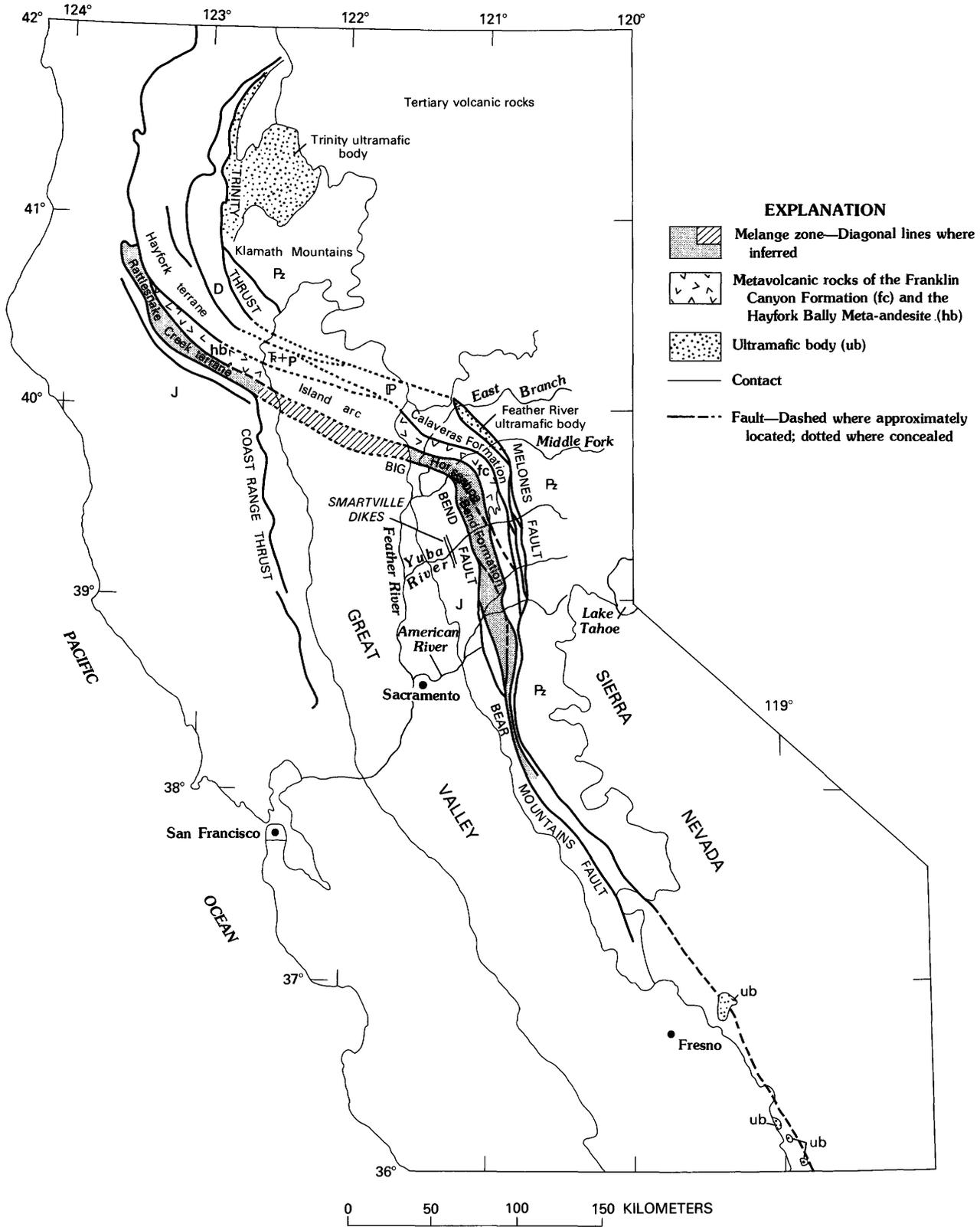


FIGURE 2.—Major structural zones of northwestern Sierra Nevada and correlations with Klamath Mountains. Modified from U.S. Geological Survey and California Division of Mines and Geology (1966). J, Jurassic; T, Triassic; P, Permian; P, Pennsylvanian; D, Devonian; Pz, Paleozoic.

Melones fault zone, from late Paleozoic metasedimentary and metavolcanic rocks on the west. Triassic rocks overlie the Paleozoic rocks in the south-central part of the area. Farther west the late Paleozoic rocks are separated from Jurassic metamorphic rocks (the Bloomer Hill Formation; Hietanen, 1977) by another major suture along the Big Bend fault zone and associated melange. The Jurassic metavolcanic rocks are at the north end of the western Jurassic belt.

The late Paleozoic rocks are thus exposed between two major sutures in an arcuate segment of the western metamorphic belt of the northern Sierra Nevada (fig. 2). The late Paleozoic rocks, from east to west, are divisible into three subunits that differ in lithology, origin, and environment of deposition but could be coeval: (a) interbedded metachert and phyllite, including minor metavolcanic rocks (the Calaveras Formation, pl. 1); (b) a series of metamorphosed basalt, andesite, dacite, sodarhyolite, and tuff (the Franklin Canyon Formation); and (c) interbedded metasedimentary and metavolcanic rocks (the Horseshoe Bend Formation). All these metamorphic rocks are intruded by Jurassic and Cretaceous plutonic rocks.

The total width of the arcuate Paleozoic segment between the Big Bend and Melones faults is about 40 km in the northwestern part of the study area but less than 30 km along its south boundary. Along the North Yuba River at the south border of the study area a section of the Calaveras Formation is only about 2 km wide; some metavolcanic rocks of the Franklin Canyon Formation have been pinched out by faulting, and some are overlain by Triassic metasedimentary rocks. On the "Geologic map of California, Chico Sheet," Burnett and Jennings (1962) show relations that suggest that the Franklin Canyon Formation may pinch out 1.5 km farther south. On their map, Burnett and Jennings showed a belt, about 12 km wide, of Paleozoic metasedimentary rocks between the Melones fault zone and the southern extension of the Camel Peak fault where it crosses the American River, 30 km to the south at lat 38°10' N. On "Geologic map of California, Sacramento sheet," Strand and Koenig (1965) showed that this belt pinches out about 10 km south of the 39th parallel. Clark (1976) mapped the eastern part of this belt as Mesozoic metavolcanic rocks and the western part as Jurassic rocks, separated farther north from the Paleozoic belt by a fault. Clark's work was subsequently used in compiling the "Geologic map of California" (Jennings, 1977), and accordingly the Paleozoic belt was shown to wedge out at lat 39°10' N.

In the Feather River area (pl. 1) the metasedi-

mentary and metavolcanic rocks of the westernmost unit, the Horseshoe Bend Formation, are cut by many parallel faults and form an imbricated melange containing intercalated long sheetlike bodies of serpentine. Similar long bodies of ultramafic rocks shown east of the southern extension of the Big Bend fault (Burnett and Jennings, 1962; Strand and Koenig, 1965) suggest that the zone of melange continues southward. This zone probably traces into the melange mapped by Duffield and Sharp (1975) between lat 38°20' and 38°30' N.

CALAVERAS FORMATION

The Calaveras Formation consists of interbedded metachert and phyllite, minor limestone, and some metavolcanic rocks. The layers of metachert range from 5 to 500 m in thickness and those of interbedded phyllite, from 2 to 1000 m. The metachert is thin bedded, light to medium gray, and forms beds 5-50 mm thick composed of 95-100 percent quartz. These beds are typically separated by thin (1-5 mm thick) layers of brown micaceous material. Thick phyllitic layers are interbedded at irregular intervals. The quartz-rich layers are recrystallized to fine- to medium-grained granular quartzite in which grain size increases and color lightens as recrystallization becomes more thorough toward the plutons and generally also toward the south. The micaceous laminae contain muscovite, chlorite, and (or) biotite in addition to quartz; disseminated magnetite is common in many layers.

The phyllitic layers are greenish or brownish gray and consist of quartz, muscovite, chlorite, and (or) biotite. Magnetite, hematite, pyrite, rutile, and sparse tourmaline occur as accessory minerals. Disseminated graphite and magnetite blacken some layers. Cordierite, andalusite, staurolite, and garnet occur locally near the plutons.

A layer of gray coarse-grained marble, 50-70 m thick and exposed continuously over 5 km, is interbedded with metachert in the Onion Valley quadrangle. This layer contains conodonts no older than Pennsylvanian and no younger than Permian (Hietanen, 1981). Other age determinations, given below show that the rocks must be Pennsylvanian.

The Calaveras Formation is isoclinally folded and strongly deformed. Micaceous minerals parallel the foliation, which transects the bedding at the crests of folds and parallels the bedding along the flanks. Two, or rarely three, sets of lineations occur in some outcrops (Hietanen, 1973a), one of which generally parallels the major (Nevadan) north-northwest-trending fold axis; two others either parallel the axes of minor folds (northwest or northeast trending) or

appear as a wrinkling of the plane of foliation. Strong stretching of minerals parallel to lineation is common. These relations suggest that the Calaveras Formation sustained at least two periods of deformation. In many outcrops, however, only one set of folds is apparent; either the earlier structures were destroyed, or the two periods of deformation were coaxial.

The folded bedding of the Calaveras Formation is cut by a large round body of amphibolite (pl. 1) in which primary concentric structures, foliation and orientation of long hornblende prisms, are well preserved, even if lightly overprinted by later regional (Nevadan) north-northwest-trending structures that appear as a fine wrinkling of the plane of foliation. The minimum age of this hypabyssal body, determined by K-Ar methods on hornblende, is 248 m.y. (Hietanen, 1980). This and a somewhat older age of 271 m.y. reported by Standlee (1978) indicate an Early Permian time for the emplacement of this mass and consequently the earliest Permian time for the first period of deformation of the Calaveras Formation. Together with the conodont evidence, these considerations prove that the Calaveras Formation in the study area is Pennsylvanian. A Carboniferous age for the Calaveras was given by Turner (1898) on the basis of crinoid stems and foraminifers, but the significant species he used are no longer considered definitive.

Three large and several small elongate or stratiform bodies of metavolcanic rocks are interbedded with metasedimentary rocks of the Calaveras Formation; the two large bodies in the north may overlie the metasedimentary rocks. The bodies consist mainly of basaltic meta-andesite that is recrystallized to an actinolite-chlorite-epidote-albite-leucoxene rock with or without quartz, chalcopyrite, magnetite, and hematite. Relict spherulitic textures and remnants of clinopyroxene and green hornblende occur in places. In the gorge of Canyon Creek, agglomeratic layers interbedded with massive-appearing basaltic meta-andesite are gently folded and have a well-developed axial-plane cleavage. In their longest dimensions the subangular andesitic fragments parallel either the bedding or the foliation. In the border zone of the large round amphibolite body, metavolcanic rocks lithologically similar to some of these layers are interbedded with the metasedimentary rocks. The amphibolite is a hypabyssal dome that probably intruded its own volcanic-sedimentary cover shortly after eruption of the volcanic rocks.

Most small bodies of metavolcanic rocks within the Calaveras Formation consist of metatuff,

commonly bedded and well foliated. Parallelism of structures with the metasedimentary host rocks indicates coeval deposition and a common deformation for these small metavolcanic bodies and the metasedimentary rocks, which were dated as Pennsylvanian (Hietanen, 1981). These dates and structural relations indicate that the volcanic activity in this area started during Pennsylvanian and continued to Permian time.

FRANKLIN CANYON FORMATION

The Franklin Canyon Formation includes metavolcanic rocks that range in composition from basaltic and andesitic to dacitic and sodarhyolitic and may range in age from late Paleozoic to Triassic(?) (Hietanen, 1981). The rocks form a well-defined geologic unit between two major sutures, the Dogwood Peak and Camel Peak faults. Minor lenticular bodies of metasedimentary rocks, mainly phyllite, are interbedded with the metavolcanic rocks. The west end of this unit, formerly mapped as the Duffey Dome Formation (Hietanen, 1973a), a name now abandoned, consists of metabasalt that has been recrystallized to amphibolite. Green hornblende and albitic plagioclase are the major constituents of this rock, and quartz, chlorite, and epidote are minor constituents.

The meta-andesite of the Franklin Canyon Formation contains more calcium and less iron and magnesium than the metabasalt (Hietanen, 1973a, table 1). The major constituents of the meta-andesite are actinolite, light-green hornblende, epidote, albite, chlorite, and leucoxene. The metadacite that makes up about 50 percent of the central part of the formation contains quartz phenocrysts and fewer dark minerals than the meta-andesite. In the metasodarhyolite, abundant quartz and albite occur as phenocrysts and in the groundmass; other constituents are muscovite, biotite, chlorite, and minor epidote. Metatuffs of various compositions are interbedded with these metavolcanic rocks; most of the metatuffs are distinctly bedded, folded, and deformed.

A continuous layer of andesitic metatuff, well exposed along Slate Creek and extending northward to American House, separates a thick homogeneous unit of meta-andesite in the southeastern part of the Franklin Canyon Formation from more silicic metavolcanic rocks of the northwestern part. This southeastern meta-andesite could be younger than the rocks of the northwestern part for the following reasons:

(1) Small masses of metagabbro, metadiorite, and metatrandhjemite, which are deep-seated equiva-

lents of the metavolcanic rocks (Hietanen, 1973a, 1976), intrude only the northwestern part of the formation (pl. 1). These masses are strongly deformed in a north-northwesterly direction, whereas the overlying andesitic metatuff that forms the base of the homogeneous meta-andesite is gently folded and less deformed.

(2) Much of the homogeneous meta-andesite is less deformed and less thoroughly recrystallized than the meta-andesite of the northwestern part of the formation. Relicts of primary minerals, such as augite, occur in the southeastern meta-andesite.

(3) Middle and Late Triassic metasedimentary rocks overlie and possibly interfinger with the southeastern homogeneous meta-andesite along the North Yuba River. These metasedimentary rocks, which are much less deformed and less thoroughly recrystallized than the Paleozoic rocks, contain radiolarians that were determined to be Triassic by David Jones (Hietanen, 1981).

These structural relations suggest that some volcanic rocks in the southeastern part of the Franklin Canyon Formation may be as young as Triassic and that the northwestern part is older, presumably late Paleozoic. If coeval with volcanic rocks within the Calaveras Formation, at least some of the volcanic rocks of the Franklin Canyon Formation are Permian as are the amphibolite and associated metavolcanic rocks.

As discussed earlier, the chemistry of the Franklin Canyon Formation (Hietanen, 1973b, 1975, 1976, 1981) indicates that the first magmas were generated early in an island-arc environment. The potassium content of the rocks is low, commonly less than 0.5 weight percent. All the rocks belong to the calcalkaline suite, and most have a high calcium content and an $\text{FeO}^{\text{total}}/\text{MgO}$ ratio between 1 and 3. All the rocks are relatively rich in Al_2O_3 and poor in MgO (fig. 3). During metamorphism, many layers were depleted in silicon and alkalis and enriched in calcium, and some layers were also enriched in iron and magnesium; thus a direct comparison of the percentages of these elements in the Feather River rocks with those present in unaltered volcanic rocks is uncertain. Nevertheless, all these meta-volcanic rocks can be identified under the microscope as metamorphosed members of the calcalkaline andesite-sodaryolite suite. The normative orthoclase content is generally very low (figs. 4A, 4B).

HORSESHOE BEND FORMATION

The Horseshoe Bend Formation (Permian?), the westernmost unit of late Paleozoic rocks, consists of interbedded metavolcanic and metasedimentary

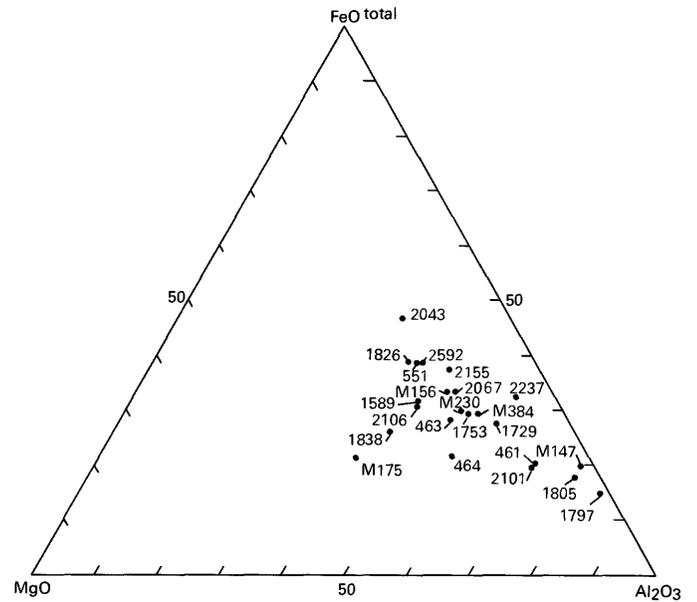


FIGURE 3.—Relative contents of $\text{FeO}^{\text{total}}$, MgO, and Al_2O_3 in metavolcanic rocks of the study area. Numbers refer to analyses in Hietanen (1973a, 1977, 1981); those with prefix "M" are from Hietanen (1951).

rocks (Hietanen, 1977). The metavolcanic rocks, mainly metabasalt including smaller amounts of meta-andesite and metarhyolite, make up most of the northwestern part of the formation, whereas metasedimentary rocks are more common in the southeastern part (pl. 1; Hietanen, 1973a, pl. 2; 1976, pl. 1; 1977, pl. 1). Long thin bodies of ultramafic rocks, which probably originated as pieces of oceanic lithosphere or mantle, lie within and near faults that have sliced this formation. The map pattern suggests a large-scale imbricated and strongly deformed melange, widely accepted as having developed in subduction zones.

The metasedimentary rocks include layers of quartzite, metachert, phyllite, and metagraywacke. Discontinuous layers of white marble are interbedded with phyllite and quartzite; no conodonts were found in these marble layers. Most of the white granular quartzite was deposited as quartz sand; grains are polygonal and rounded, and micaceous minerals, the common minor constituents, are scattered throughout most layers. Metachert has preserved its primary thin-bedded structure during the recrystallization to white granular quartzite. Layers of fine-grained light-gray quartzite are most likely weathering products of rhyolitic tuff. Most of the clasts in the lithic metagraywacke are fine-grained metachert and quartzite, about one-third are phyllite, and some are metavolcanic rocks. The matrix contains tuffaceous material. The source rocks of the quartzite and

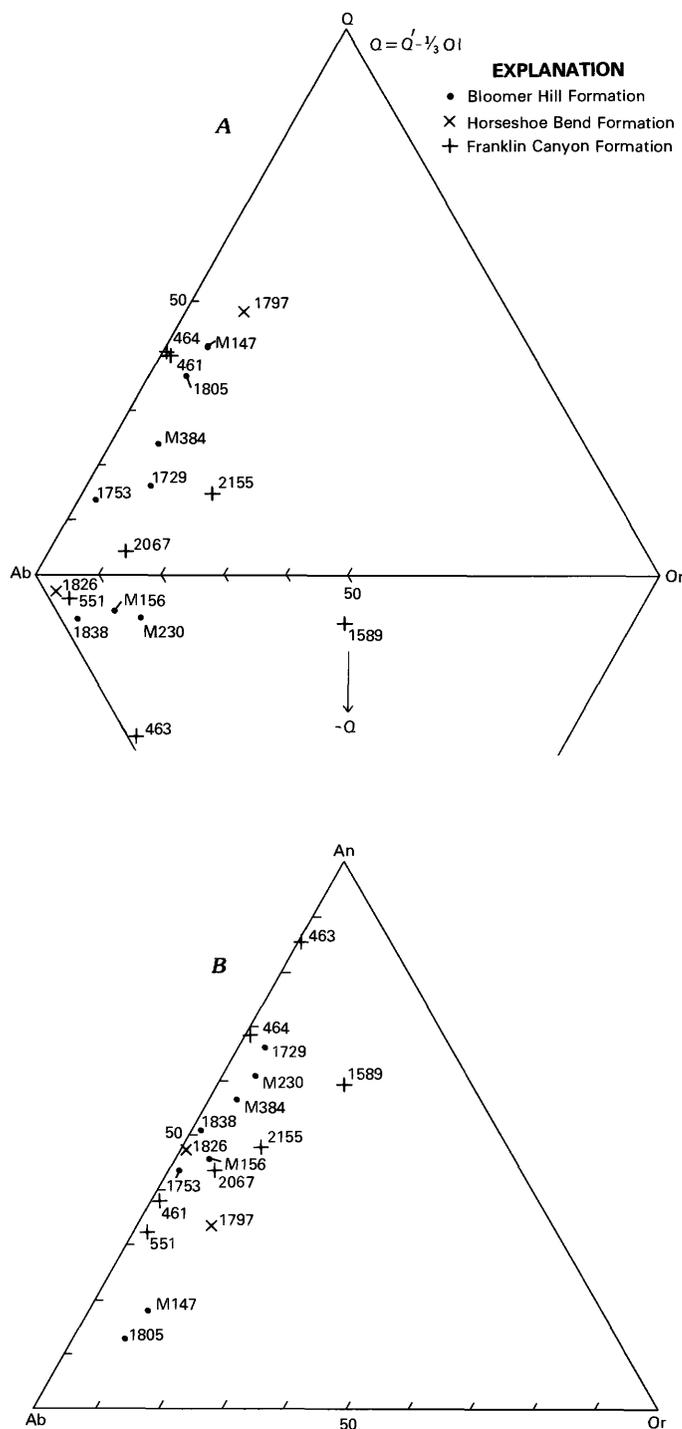


FIGURE 4.—Normative molecular Ab-Or-Q and Ab-Or-An ratios in metavolcanic rocks of the study area. Numbers refer to chemical analyses in Hietanen (1973a, 1977, 1981); those with prefix "M" are from Hietanen (1951). A, Albite (Ab), orthoclase (Or) and quartz (Q). B, Albite (Ab), orthoclase (Or), and anorthite (An).

lithic metagraywacke were probably the Franklin Canyon and Calaveras Formations and other Paleozoic rocks to the east. Proximity of the source is indicated by the subangularity of the clasts.

Most of the metavolcanic rocks consist of metabasalt and basaltic metatuff. Andesitic and dacitic layers and lenses are few and small except between the Merrimac and Hartman Bar plutons, where they form 85 percent of the metavolcanic rocks. Only about 10–15 percent of the metavolcanic rocks are rhyolitic. Tuffaceous layers of all compositions are distinctly bedded and foliated.

The mineralogy and chemical composition of the metabasalt of the Horseshoe Bend Formation are similar to those of metabasalt of the Franklin Canyon Formation. Green hornblende and albitic plagioclase are the major constituents, and epidote, quartz, and magnetite occur in varying quantities. Some of the rhyolitic rocks contain more potassium (as much as 10 weight percent) than is common in sodarhyolitic rocks of the Franklin Canyon Formation.

BLOOMER HILL FORMATION

To the southwest of the zone of melange (the Horseshoe Bend Formation) in the Big Bend area are metavolcanic rocks chemically similar to those of the Franklin Canyon Formation, but they are much less deformed and less thoroughly recrystallized. These rocks, the Bloomer Hill Formation, range in composition from metabasalt and meta-andesite to metadacite and metasodarhyolite. The normative orthoclase content is low in all samples analyzed (fig. 4). Volcanic breccia, subangular to rounded bombs, and agglomeratic and tuffaceous layers are common. These textural features, together with the calcalkaline composition, suggest an island-arc environment for the eruption of rocks of the Bloomer Hill Formation (Hietanen, 1977). These rocks form the north end of the western Jurassic belt and are probably continuous with the Late Jurassic rocks to the west and south.

TECTONIC INTERPRETATION

A narrow belt of metachert and phyllite, deposits typical of ocean floors (the Calaveras Formation), between the Melones fault and the island-arc-type metavolcanic rocks of the Franklin Canyon Formation, is a remnant of a wide basin that existed between the continental margin (the Shoo Fly Formation) and the Paleozoic and Triassic(?) island arc (the Franklin Canyon Formation) on the west (fig. 5). Most of the floor of this basin was subducted under the continental margin along the Melones fault zone during late Paleozoic time. The belt of island-arc rocks was probably a result of a subduction along the Big Bend fault zone. This belt was greatly narrowed by deformation, faulting, and underthrusting along

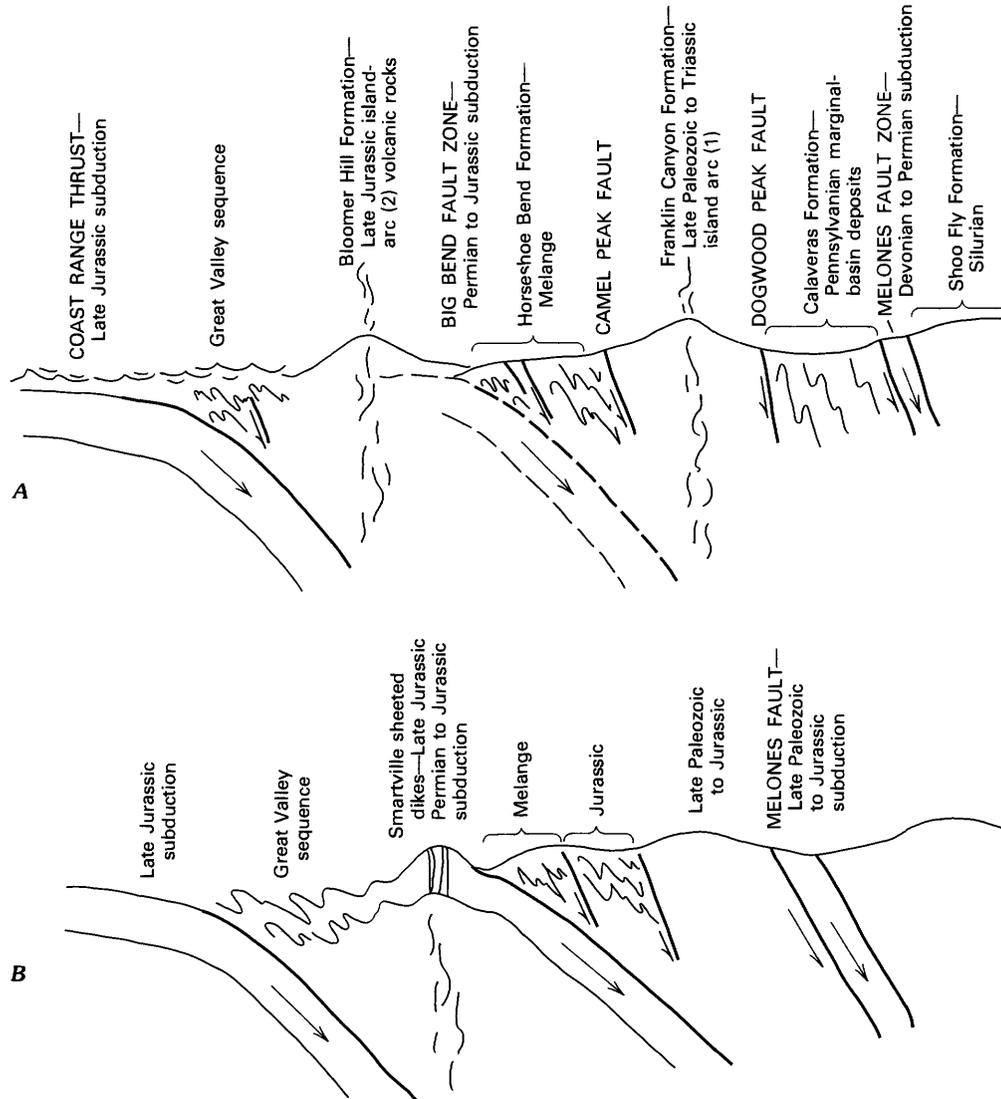


FIGURE 5.—Sketches showing possible evolution of the Sierra Nevada suture system and time and environment of deposition of metasedimentary and metavolcanic rocks. Units between Big Bend and Melones fault in 5A are generalized from those shown in cross Section A-A, plate 1. A, Lat 39°35' N. B, Lat 39°15' N.

Coast Ranges. The site of deposition of the metasedimentary and metavolcanic rocks of the Horseshoe Bend Formation became first an interarc basin and later a zone of collision between the arcs.

The Horseshoe Bend Formation includes numerous elongate bodies of ultramafic rocks, some accompanied by metagabbro, that probably represent slabs of mantle and oceanic crust that later, during Jurassic time, became the floor of an interarc basin. These slabs were pushed up or tilted along and near faults and fractures in the zone of subduction, later a zone of collision between the Jurassic and Paleozoic island arcs. The metasedimentary and metavolcanic strata of the Horseshoe Bend Formation also were broken into blocks and sheets that were deformed and displaced during subduction and collision. The

bordering fault zones. In the southern part of the study area (pl. 1) a dismembered ophiolite sequence of ultramafic rocks, metagabbro, and metadiorite border the island-arc rocks on the west. This sequence is probably a remnant of an oceanic lithosphere on which the island arc was built. Smaller pieces of a similar dismembered ophiolite sequence occur along the Camel Peak fault zone farther northwest. Interbedded volcanic rocks, graywacke, shale, and minor limestone of the Horseshoe Bend Formation were deposited in shallow water on the west (ocean) side of the island arc volcanoes (island arc 1, fig. 5). During Jurassic time a second island arc (island arc 2, fig. 5) was formed some distance to the west (the Bloomer Hill Formation; Hietanen, 1977) as a result of stepping of the Benioff zone farther westward to the

present stratigraphy is therefore not the primary one everywhere. For example, a large occurrence of lithic metagraywacke and associated metasandstone south of Clipper Mills is structurally discordant with the surrounding rocks. The metavolcanic rocks between the Merrimac and Hartman Bar plutons are similar to those of the Franklin Canyon Formation to the east whereas on the west side of the Merrimac pluton, 8 km to the west paralleling the regional trends, metabasalt is the major rock type. Nevertheless, many individual layers of metasedimentary rocks and volcanic units can be traced for a distance of several kilometers, and all the rocks were folded and deformed together. The bedding is well preserved in most of the quartzite, metachert, and metatuff. True melange, such as rounded fragments of metachert in metavolcanic rocks and lenses of marble in phyllite, was observed only in a few places. The elongate bodies of ultramafic and mafic rocks were deformed and recrystallized with the metasedimentary and metavolcanic rocks. The present distribution of rock types (pl. 1; Hietanen, 1973a, pl. 1; 1976, pl. 1) suggests a large-scale strongly deformed imbricated melange containing about equal amounts of metasedimentary, metavolcanic, and ultramafic rocks.

All these late Paleozoic and Triassic(?) rocks are exposed between two major sutures, the Melones and Big Bend fault zones, that farther south, near the 39th parallel, join to form a major structural zone bordered by the Melones and Bear Mountains faults. There, late Paleozoic rocks of the Feather River area wedge out, and Jurassic rocks lie adjacent to the Melones fault zone (Jennings, 1977). Subduction of all these late Paleozoic rocks under the continental margin in the south could account for the greater abundance of granitic rocks in the Sierra Nevada south of the 39th parallel.

Age determinations on gabbroic rocks along the Melones fault zone indicate that subduction along that zone continued intermittently from Middle Devonian to Jurassic time. Standlee (1978) reported a 387.4 ± 7.6 -m.y. $^{39}\text{Ar}^{40}\text{Ar}$ age on hornblende in dikes that cut cumulate gabbro near Onion Valley. Saleeby and Moores (1979) reported zircon ages of 275–313 m.y. for metaplagiogranite intruding the Feather River ultramafic body; these ages make the ultramafic body even older. Its mantle origin is supported by relict layering at an angle to the regional trends. Similar layering is well preserved along Onion Valley Creek and Washington Creek, where lenticular clusters of olivine form thin crude layers in pyroxene rock that is partially altered to colorless amphibole (Hietanen, 1981). A K-Ar age of 236 ± 4 -m.y. on hornblende in mafic schist from along the Rich

Bar fault on the west side of the Feather River ultramafic body was reported by Weisenberg and Ave Lallemand (1977). Hornblende in gabbro on the east side of the ultramafic mass along the Goodyears Creek fault yielded a K-Ar age of 285 ± 8 -m.y. (Hietanen, 1981). In contrast, the age determinations on rocks from along the Melones fault zone farther south are younger. Permian and Triassic thrusting of the Shoo Fly Formation over the Calaveras was suggested by Schweickert (1977). Most other age determinations are Jurassic, owing to igneous activity and resetting of the K-Ar geologic clock during the Nevadan orogeny.

Jurassic ages of 161.9 ± 8 -m.y. ($^{40}\text{Ar}_{\text{rad}} = 0.60354 \times 10^{-9}$ mol/g; 0.247, 0.248 weight percent K_2O , 44.7 percent $^{40}\text{Ar}_{\text{rad}}$ and $1.48.0 \pm 7.4$ -m.y. ($^{40}\text{Ar}_{\text{rad}} = 0.54972 \times 10^{-9}$ mol/g, 0.247, 0.248 weight percent K_2O , 50.2 percent $^{40}\text{Ar}_{\text{rad}}$) were determined by Wendy Hoggatt on hornblende in inhomogeneous hornblende gabbro (sample 2637) from along the Camel Peak fault, which separates the Franklin Canyon Formation from imbricated melange of the Horseshoe Bend Formation on the west. This hornblende gabbro is exposed on the east side of a large elongate body of ultramafic rocks and is probably part of an ophiolite sequence. In the gorge of Slate Creek (loc. 2637, pl. 1) the gabbro is fine- to medium-grained hornblende-plagioclase rock containing some quartz, magnetite, and segregations of epidote. Hornblende forms bluish-green to green subhedral prisms that are either arranged at random or subparallel to a weak foliation. Much of the plagioclase (An_{28}) and quartz are granulated and form an interstitial mosaic that includes small grains of hornblende and epidote. The optical properties and chemical composition of the hornblende (Hietanen, 1981, sample 2637, table 2) resemble those of hornblende in meta-igneous rocks of this area (Hietanen, 1974). The 162–148 m.y. age probably represents the time of recrystallization during the tectonic events rather than the time of emplacement of the gabbro.

The effect of the Jurassic deformation on all earlier structures makes the recognition of earlier deformations difficult if not impossible. Two or three sets of lineations and minor folds on axes parallel to them, however, can be observed in many outcrops along the Middle Fork of the Feather River, along Slate Creek, and along Bear Creek and vicinity. Where the overprint was either coaxial or strong enough to destroy earlier structures, the rocks appear to have undergone only one period of deformation. For example, along the North Yuba River, Cebull and Russell (1979) found that the cleavage in the blueschist within the Melones fault zone parallels

regional structures and that no trace of older structures, which, however, are mappable in parts of the area to the north, exists (Hietanen, 1973a, 1981). Ave Lallemand, Weisenberg, and Standlee (1977) suggested that the older structures along the Melones fault zone between the North Fork of the Feather River and the American River were formed during the Sonoma orogeny and that the younger north-northwest-trending cleavage formed during the Nevadan orogeny.

CORRELATION WITH THE KLAMATH MOUNTAINS

The Paleozoic age of the Feather River ultramafic body and the late Paleozoic age of the Calaveras Formation to the west suggest a broad correlation of these units with the Paleozoic Trinity ultramafic body (Davis, 1969; Irwin, 1981) and the Paleozoic and Mesozoic rocks west of it in the Klamath Mountains (fig. 2). Specifically, the sequence of meta-andesite overlain by thin-bedded metachert, metatuff, argillite, minor limestone, and mafic metavolcanic rocks of the middle and upper units of the Hayfork terrane of Irwin (1977a) suggest a broad lithologic similarity to the Franklin Canyon and Calaveras Formations in the Feather River area. In the Klamath Mountains, pods and lenses of limestone containing late Paleozoic fossils, some of Tethyan faunal affinity (Irwin, 1977b), are included in strata that contain radiolarian chert of Mesozoic age (Irwin and others, 1977). Probably, the late Paleozoic strata were broken into slabs that were incorporated into the Mesozoic melange.

In the Feather River area, most strata in the Calaveras Formation are coherent and have well-preserved bedding that can be traced in many places for more than 10 km. In contrast, the Horseshoe Bend Formation is broken up into long slabs that are separated by long thin bodies of ultramafic rocks. This structure and the great variety of metavolcanic and metasedimentary rocks present suggest a melange similar to that in the Rattlesnake Creek terrane of Irwin (1977a) in the Klamath Mountains. Moreover, the Horseshoe Bend Formation and the Rattlesnake Creek terrane are separated by a major fault zone from Late Jurassic rocks on the west and thus they occupy a comparable tectonic position.

The lenticular fault pattern typical of the northwestern Sierra Nevada north of lat 38°30' N. (fig. 2) probably continues toward the Klamath Mountains under the Great Valley sequence and Cenozoic volcanic rocks and accounts for the differences between the lithologic units of these two areas. For example, Devonian rocks of the central metamorphic belt and

the Hayfork terrane of the Klamath Mountains probably pinch out eastward, whereas the Pennsylvanian Calaveras Formation of the Feather River area pinches out westward (fig. 2). The Hayfork Bally Meta-andesite (fig. 2) could be continuous with the metavolcanic rocks of the Franklin Canyon Formation (fig. 2). Overlap and interfingering of the Franklin Canyon Formation along the North Yuba River by and with Triassic metasedimentary rocks suggest a Triassic age for the southern part of the Franklin Canyon Formation. The late Paleozoic to Triassic calc-alkaline island-arc volcanic activity in the Klamath Mountains and northwestern Sierra Nevada occurred during the Sonoma orogeny in the eastern Cordillera (Burchfiel and Davis, 1975); both events indicate increased tectonic activity during convergence of the North American and Pacific plates.

CORRELATION WITH SOUTHERN STRUCTURES

The major structures, the Melones and Big Bend fault zones, continue southward from the North Yuba River (Burnett and Jennings, 1962; Strand and Koenig, 1965; Clark, 1976) and join at lat 38°45' N. to form the southern section of the major structural zone bordered by the Melones and Bear Mountains faults (fig. 2). Geologic maps (for example, Burnett and Jennings, 1962; Clark, 1976) show only plutonic rocks in the area where the southern extension of the Horseshoe Bend Formation should be between the North Yuba River (at lat 39°30' N.) and Deer Creek (at lat 39°15' N.). Farther south, Clark (1976) showed a variety of Paleozoic and Mesozoic rocks in this structural zone, and still farther south, between lats 38°20' N. and 38°33' N., Duffield and Sharp (1975) mapped a zone of melange, 3 km wide, between the Bear Mountains fault and metavolcanic rocks of the Logtown Ridge Formation; this zone is bordered by the Mariposa Formation and the Melones fault on the east. The southern extension of this melange zone includes some limestone lenses containing Permian fusulinids of Tethyan faunal affinity. Apparently a continuous belt of melange separates Late Jurassic rocks on the west from the older rocks on the east. Subduction along this zone probably started in late Paleozoic and continued to Late Jurassic time; the main phase occurred during the Nevadan orogeny.

Moores, Day, and Xenophontos (1979) have mapped sheeted dikes paralleling regional north-westward trends in the Jurassic Smartville ophiolite complex, most likely a marginal-basin complex. The dikes are in the core of an antiformal complex flanked on either side by pillow lava that is overlain by meta-andesite. The 159- to 175-m.y. age for the dikes (Saleeby and

Moore, 1979) suggests emplacement during Late Jurassic time which was the period of volcanism west of the Big Bend fault zone (the Bloomer Hill Formation; Hietanen, 1977) and the time of the beginning of plutonism east of it (Hietanen, 1981). Surface expression of the Late Jurassic and Cretaceous subduction that gave rise to the formation of these Late Jurassic magmas is probably in the Coast Ranges, on the west side of the Great Valley (Coast Range thrust, fig. 5). Subduction along the Big Bend melange zone continued to Late Jurassic time, and differences in the velocity of subduction between the eastern and western parts of the marginal-basin floor could have created tension that produced the Smartville fracture zone (fig. 5B). Farther north, Jurassic island-arc-type metavolcanic rocks of the Bloomer Hill Formation exposed in this zone (fig. 5A), cover the possible northward continuation of the fracture zone.

Schweickert and Cowan (1975), who summarized much of the work done in the southern section, have suggested a plate-tectonic model. In their sketch map (Schweickert and Cowan, 1975 p. 1330, fig. 7) all late Paleozoic rocks west of the Melones fault in the Feather River area are shown as melange and an island-arc sequence is shown south of the North Yuba River between the melange and the Smartville ophiolite complex to the west. However, in the Feather River area a zone of melange (the Horseshoe Bend Formation, pl. 1) lies between the island-arc rocks (the Franklin Canyon Formation) on the east and the north end of the Jurassic belt (the Bloomer Hill Formation) on the west. The Calaveras Formation east of the island-arc rocks is coherent and has a well-preserved bedding. Schweickert (1976) suggested that these Calaveras rocks on the west side of the Melones fault could be part of the missing Calaveras Formation farther south, cut off by the Melones fault and transported 500-600 km north during early Mesozoic time. No evidence for this interpretation was found in the study area. On the contrary, inclusion in the Melones fault zone near parallel 39°40' N. of pieces of the Silurian Shoo Fly Formation exposed due east of the fault zone and of Permian amphibolite exposed due west of the fault makes lateral north-southward transportation difficult, if not impossible. Rather, underthrusting to the east of several lithologic units explains the tectonic features as well as the generation of volcanic and plutonic magmas in this area.

SUMMARY OF TECTONIC AND PLUTONIC EVENTS

Detailed geologic studies in the Feather River area

(Hietanen, 1973a, b; 1976; 1977; 1981) suggest that the movement along major fault zones was underthrusting to the east of several coherent lithologic units that caused tectonic accretion to the continental American plate of island arcs, interarc and marginal-basin floors, and slabs of oceanic crust and mantle. Subduction of the Pacific Ocean floor that later became a marginal-basin floor (the remaining strip is now covered by the Calaveras Formation) along the Melones fault started in Devonian and continued into Jurassic time. The main late Paleozoic and early Mesozoic subduction was along the Big Bend fault zone, where a wide zone of imbricated melange was formed (the Horseshoe Bend Formation). The island-arc volcanism to the east (the Franklin Canyon Formation) was a result of this subduction.

The two major sutures, the Melones and Big Bend fault zones, join to form a major structural zone south of lat 38° 30' N. containing melange between the Melones and Bear Mountains faults. On a large scale the regional structure between lat 38°30' and 40°30' N. is characterized by a similar imbricated and lenticular fault pattern, typical of the Horseshoe Bend Formation. The width of this system of major sutures in the western Sierra Nevada is 7 km at lat 38°30' N. and 40 km near the 40th parallel, where its northerly trends bend northwestward toward the Klamath Mountains. There, a zone of Paleozoic to Middle Jurassic rocks between Late Jurassic rocks on the west and early Paleozoic rocks on the east side of the Trinity thrust is about 55 km wide. The Rattlesnake Creek melange (Irwin, 1977a) in the westernmost part of this zone occupies the same tectonic position as the Horseshoe Bend Formation in the Feather River area; both units are separated by a major suture from Late Jurassic rocks on the west and faulted against the metavolcanic belt on the east. The Trinity thrust that in the Klamath Mountains separates early Paleozoic from younger rocks to the west can be correlated with the Melones fault in the Feather River area. In the south the ultramafic rocks, shown on the "Geologic map of California" (Jennings, 1977) on the west edge of the Sierra Nevada batholith between the 36th and 37th parallels, align structurally with the southern continuation of this system of sutures and probably represent remnants of ophiolite that were not engulfed by younger granite. The total length of this Sierra Nevada suture system, from the Garlock fault in southern California to the Klamath Province in Oregon, is about 1,000 km. The suture system was formed along the continental margin and involved stepping of the Benioff zone from the Melones to the Big Bend fault zone during late Paleozoic time.

The Paleozoic metavolcanic rocks, shown on the "Geologic map of California" (Jennings, 1977) 10-15 km east of the Melones fault and ranging in composition from rhyolitic to andesitic rocks, were most likely a result of subduction along the Sierra Nevada suture system. Later, during Late Jurassic time, the Benioff zone stepped farther westward to the Coast Range thrust. Subduction along that zone gave rise to Late Jurassic magmas in the Sierra Nevada.

The late Paleozoic to Jurassic structures in the Feather River area are modified and cut by Late Jurassic to Early Cretaceous plutons. The plutonism between the Melones and Big Bend fault zones started in the Late Jurassic (160 m.y. ago), that is, at the time of volcanism on the west side of the Big Bend fault zone. The plutonism continued to the Cretaceous, and the potassium content of the magmas increased slightly over time. Earlier, Hietanen (1973b, 1975) suggested that these plutonic magmas were generated by large-scale partial fusion of the subducted oceanic lithosphere and a part of the continental plate above it, and by partial or total melting of deeper parts of the downfolded meta-volcanic and interbedded metasedimentary rocks.

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Extension of Sierra Nevada- Klamath Suture System into Eastern Oregon and Western Idaho

By ANNA HIETANEN

PETROLOGIC AND STRUCTURAL STUDIES IN THE NORTHWESTERN SIERRA NEVADA

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Plate-tectonic implications of a major structure zone



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EXTENSION OF SIERRA NEVADA-KLAMATH SUTURE SYSTEM INTO
EASTERN OREGON AND WESTERN IDAHO

By ANNA HIETANEN

ABSTRACT

A late Paleozoic to Jurassic suture system in the northwestern Sierra Nevada is defined by two major subduction zones, the Melones and Big Bend fault zones, and intervening zones of melange (Horseshoe Bend Formation), island-arc volcanic rocks (Franklin Canyon Formation), and shallow-water marine deposits (Calaveras Formation), all metamorphosed, deformed, and bordered by faults. This suture system continues southward to the Garlock fault and includes the Foothills fault system. In the northern part of the Great Valley, it is covered by Tertiary volcanic rocks and Cenozoic sedimentary deposits; it is well exposed farther northwest in the Klamath Mountains, where trends turn to the northeast. In the Klamath Mountains, the suture system is a 55-km-wide belt of Paleozoic and Mesozoic rocks between the Trinity ultramafic body and the Rattlesnake Creek melange. In western Oregon, Tertiary volcanic rocks cover most of this structural zone, but in eastern Oregon, late Paleozoic and Mesozoic rocks along with ultramafic bodies are exposed in uplifted areas and in windows in the John Day-Blue Mountains area. In these areas, the Paleozoic and Triassic shallow-water sedimentary rocks and island-arc-type volcanic rocks bear a resemblance to the late Paleozoic and Triassic rocks in the Sierra Nevada-Klamath suture zone, and the trends are consistently to the northeast. It therefore seems that the late Paleozoic and Mesozoic margin of the North American continent, defined by the Sierra Nevada-Klamath suture system, continues through Oregon to the Idaho batholith, forming a wide arc. The structures in Idaho suggest that the northeast trends are cut or modified by the Idaho batholith and that another set of structures trends northwest parallel to the northwestern trends that extend from northern Idaho and Washington into Canada. The Paleozoic and early Mesozoic trends do not curve around from northeast to north and northwest but rather form a cusp that, in Cretaceous time, was modified and intruded by the rocks of the Idaho batholith.

INTRODUCTION

Structural and petrologic studies in the northwestern Sierra Nevada (Hietanen, 1973a,b, 1976, 1977, 1981a) have revealed two major subduction zones, the Melones and Big Bend fault zones, with a belt of imbricated melange, the Horseshoe Bend Formation, on the northeast side of the Big Bend fault (fig. 1). Northeast of the melange, two coherent belts are exposed, a western belt of island-arc-type metavol-

canic rocks (the Franklin Canyon Formation) and an eastern one of interbedded metachert and phyllite (the Calaveras Formation of Pennsylvanian age). Contacts between these belts are faults or thrusts that trend south near the North Yuba River and curve to the northwest in the Feather River area (Hietanen, 1981b, pl. 1, fig. 2). The island-arc rocks range in composition from basaltic to sodarhyolitic and include small masses of plutonic rocks of the same composition.

The major fault zones and the zone of melange continue southward, forming a suture system (Hietanen, 1981b) between the early Paleozoic continentally derived metasedimentary rocks on the east and Late Jurassic metavolcanic and metasedimentary rocks on the west. At lat 38°30', the melange is between the Bear Mountains and Melones faults (Duffield and Sharp, 1975; Behrman, 1978); isolated remnants of melange along with some ultramafic rocks are included in granite farther south between the 36th and 37th parallels (Jennings, 1977). Behrman (1978) reports Tethyan fusulinids of Permian age from limestone blocks within the melange belt and an age older than 191 m.y. for the metamorphism. Hornblende in amphibolite included in a serpentine block yielded a K-Ar age of 302 ± 35 m.y.

Toward the northwest, the Cenozoic sedimentary deposits and Tertiary volcanic rocks cover the suture system; it is exposed again in the Klamath Mountains (fig. 1), where it separates the Late Jurassic rocks on the west from the Paleozoic rocks on the east (Irwin, 1977a, 1981). Here the trends turn northward, then northeasterly (Hotz, 1971, 1978; Irwin, 1977b; Wells and Peck, 1961). The limestone lenses in the metasedimentary formations in the western part of the suture belt have yielded late Paleozoic fossils, whereas radiolarians in the metacherts, many of which are near major faults, are Triassic and Jurassic (Irwin, 1977a, 1981). The rubidium-strontium age

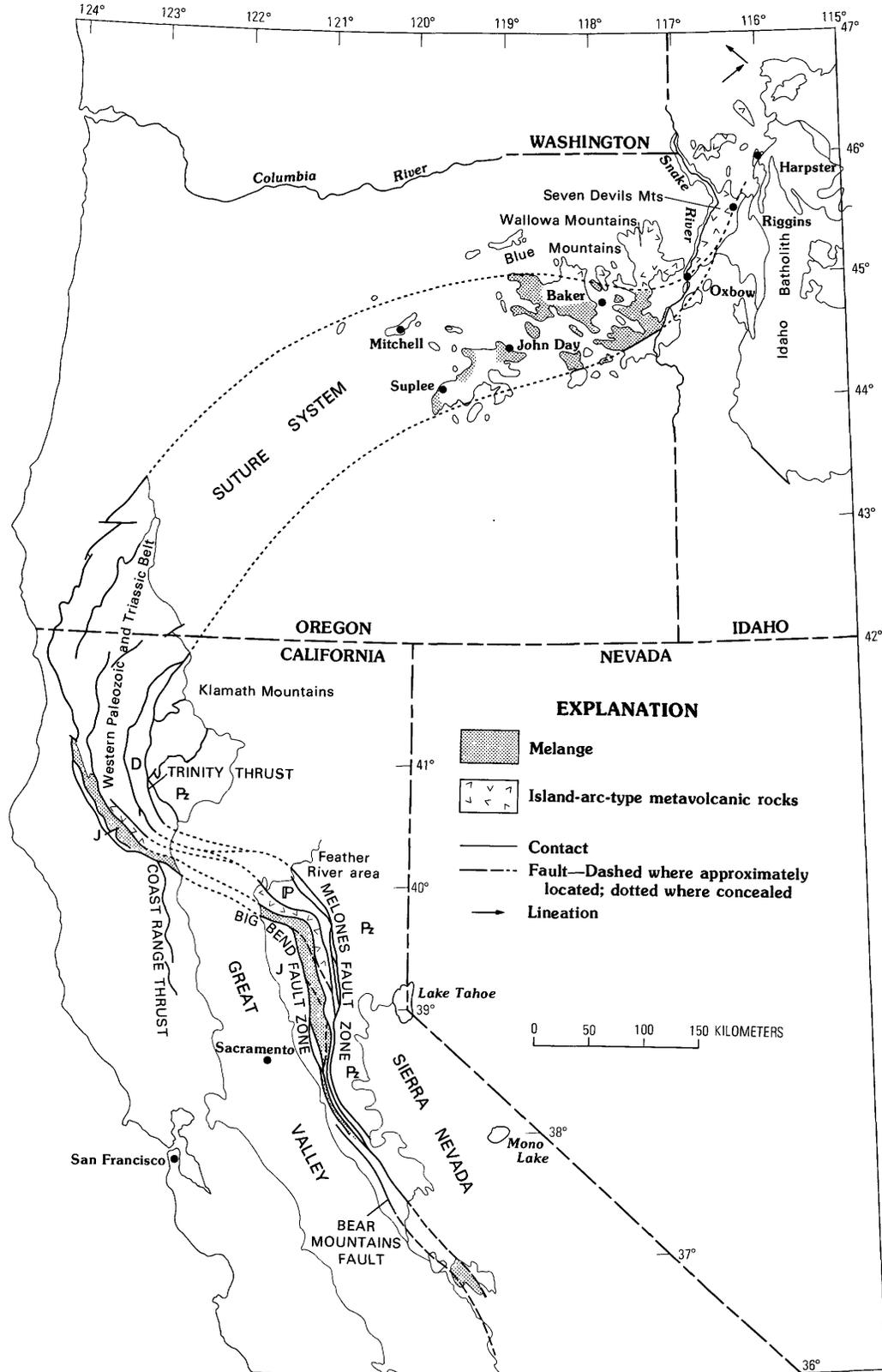


FIGURE 1.—Extension of Sierra Nevada-Klamath suture system into eastern Oregon and Idaho. Outcrop areas of pre-Tertiary rocks in Oregon and Idaho are outlined from King and Beikman (1974). Structures in California are from figure 2 in Hietanen (1981b). P₂ = Paleozoic; D = Devonian; P = Pennsylvanian; J = Jurassic.

of metamorphism of schists in the central metamorphic belt is Devonian (380 m.y.) according to Lanphere, Irwin, and Hotz (1968). Most of the plutonic rocks are Jurassic; some are Early Cretaceous (K-Ar ages 127-167 m.y.) and a few are older. The oldest age reported by Lanphere, Irwin, and Hotz (1968) is 246 m.y. and considered to be Permian. Armstrong (1978) includes this date in the Early Triassic in his revised time scale. A potassium-argon age of about 220 m.y. for a white mica in blueschist near the fault that borders the suture on the east is reported by Hotz, Lanphere, and Swanson (1977). Paleontologic ages ranging from Silurian to Jurassic for the undivided northern part of the western Paleozoic and Triassic belt (Irwin, 1981) suggest that the terrane is melange that includes large coherent blocks of various ages.

In western Oregon, east of long 122°50' (Wells and Peck, 1961), the northeastern extension of this structural zone is covered by Tertiary volcanic rocks; in eastern Oregon, late Paleozoic and early Mesozoic rocks along with ultramafic rocks are exposed in uplifted areas and in windows (Walker, 1977). In easternmost Oregon and western Idaho, they are exposed in canyons of the Snake and Salmon Rivers and their tributaries and in the Seven Devils Mountains (Hamilton, 1963, 1969; Vallier, 1967, 1974; Ross and Forrester, 1947). In these areas, the Paleozoic and Triassic shallow-water sediments and island-arc-type volcanic rocks are in many respects similar to the upper Paleozoic and Triassic rocks in the Sierra Nevada-Klamath suture system and the trends are consistently to the northeast. The major structural and petrologic features of these rocks together with their ages provide a basis for correlation, and, with northeast trends, suggest that the Sierra Nevada-Klamath suture arches through Oregon and continues to the Idaho batholith.

PALEOZOIC AND EARLY MESOZOIC ROCKS IN EASTERN OREGON AND WESTERN IDAHO

The Paleozoic and early Mesozoic rocks in eastern Oregon are generally less metamorphosed than those in the Sierra Nevada and Klamath Mountains. Well-preserved sections in several localities have yielded fossils for dating and subdivision.

SEDIMENTARY SEQUENCES

A poorly exposed section containing excellently preserved fossils southeast of Paulina, in the headwaters of Grindstone and Twelvemile Creeks, southwest of Suplee (fig. 1), was studied and dated by Merriam and Berthiaume (1943), who recognized the

following formations: the Coffee Creek Formation (marine limestone and sandstone) of Early Carboniferous age overlain by the Spotted Ridge Formation (chert, terrestrial or estuarine sandstone, conglomerate, and mudstone) of Pennsylvanian age, both overlain by the Coyote Butte Formation (limestone and sandstone) of Permian age, later dated by Skinner and Wilde (1966) as earliest Permian (Wolfcampian). All these rocks were folded before the upper Triassic conglomerate and sandstone in the Begg Formation of Dickinson and Vigrass (1965) were deposited. A second Jurassic deformation affected the Upper Triassic and all older rocks.

The Paleozoic and Triassic(?) sedimentary sequences continue north-northeast (Brown and Thayer, 1977); they are gently folded and cut by numerous faults (Buddenhagen, 1967). Near Suplee, quartz keratophyre and tuffaceous layers are interbedded with marine limestone and chert, that, according to Dickinson and Vigrass (1965), were deposited in shallow to moderate depths in shelf seas. The limestone near Suplee was correlated by them with the Permian Coyote Butte Formation and with the limestone in the Elkhorn Ridge Argillite near Sumpter (30 km west of Baker), eastern Oregon, dated as Early Permian by Taubeneck (1955). Later, Bostwick and Koch (1962) identified Early Permian fusulinids in the Coyote Butte Formation near Suplee and Late Permian fusulinids in the Elkhorn Ridge Argillite in the Virtue Hills east of Baker (fig. 1). Merriam and Berthiaume (1943) noted the Asiatic affinity of the Coyote Butte brachiopods; a typical Tethyan fauna from a faulted limestone block 3 km east of John Day was described and dated as Early and middle Permian by Bostwick and Nestell (1967). Crystalline limestone interbedded with muscovite-chlorite-phyllite in the Mitchell quadrangle (Oles and Enlows, 1971) contains poorly preserved fusulinids that resemble those in the Permian Coyote Butte Formation. A potassium-argon age of 223 ± 3.2 m.y. on white mica from a lawsonite-bearing blueschist in the Mitchell quadrangle (Hotz and others, 1977) indicates Triassic recrystallization of these rocks.

The Elkhorn Ridge Argillite, first described and named by Gilluly (1937) in the Baker quadrangle, consists of argillite, tuff, and chert with subordinate limestone and greenstone. Tuffaceous argillite and tuffaceous limestone are common. A more highly deformed sequence of metavolcanic and metasedimentary rocks in the southern part of the Baker quadrangle was mapped by Gilluly (1937) as the Burnt River Schist. Near Snake River, these two units form a continuous sequence and have been mapped as one unit by Brooks (1978, 1979). The lithology of this unit

resembles that of the Calaveras Formation in the Feather River area (Hietanen, 1973a, 1981a).

Northwest-trending Tertiary faults have given a west-northwesterly outcrop pattern to the Elkhorn Ridge Argillite in the Baker quadrangle. However, northeasterly structural trends prevail and are dominant in the eastern part of the quadrangle, where the rocks are continuous with the argillite in the adjacent Durkee and Sparta quadrangles as mapped by Prostka (1962, 1967). The Permian rocks there have been deformed at least twice and the northeast-trending lineation and fold axes are prominent. The overlying Upper Triassic rocks are less deformed and show only planar structures. These structural relations resemble those between the Middle and Upper Triassic and older rocks along the North Yuba River in the northwestern Sierra Nevada, where the Triassic metasedimentary rocks are much less deformed than the upper Paleozoic rocks (Hietanen, 1981a).

Southwest of John Day, where the Paleozoic rocks form a chaotic mixture with the plutonic rocks of the Canyon Mountain Complex (ultramafic rocks, gabbro, quartz diorite, and albite granite), the map pattern of Thayer (1965a, b, c) is reminiscent of that of trench melange. Thayer later (1977) recognized that the Canyon Mountain complex consists of parts of an Early Permian ophiolite complex on which late Paleozoic rocks were deposited. In an early summary of sedimentary, volcanic, and intrusive sequences in central and northeastern Oregon, Thayer and Brown (1964) had pointed out that the Paleozoic rocks, ranging from Devonian to Permian in age, had been folded and metamorphosed before the emplacement of the Canyon Mountain Complex, determined as post-Wolfcampian and pre-Late Triassic. They (Thayer and Brown, 1964) stressed a complete absence of Early and Middle Triassic fossils resulting from either the unfossiliferous character of the rocks or unconformities. Early Triassic conodonts were, however, found later (Dickinson and Thayer, 1978). South of the Aldrich Mountain quadrangle (Thayer, 1956a), Wallace and Calkins (1956) mapped these rocks as the Paleozoic and Triassic(?) basement complex. The occurrence of Upper Triassic rocks within and next to the Paleozoic rocks has been described by many workers. Dickinson and Thayer (1978) summarized the lithologic associations in the John Day inlier, pointing out that the island-arc volcanic rocks, graywackes, and limestones are in a tectonic matrix of deformed ocean-floor sediments, chert and argillite. They interpret the structural relations in this way: The ultramafic and associated plutonic rocks are fragments of oceanic substratum on which Permian volcanic rocks, argillite, and chert were deposited. All

these rocks now form a melange into which Upper Triassic strata were folded and faulted in places. Vallier, Brooks, and Thayer (1978) report Permian K-Ar ages of 240-250 m.y. for the hornblende pegmatite cutting the gabbro in the Canyon Mountain Complex and a range of 186 to 234 m.y. for amphibolite blocks in adjacent melange. The overlying metasedimentary rocks are considered to be equivalent to the Elkhorn Ridge Argillite and therefore Permian and Triassic in age. Fusulinid faunas near Suplee and north of the Canyon Mountain Complex are of Early Permian age. Radiolaria from chert at Vance Creek near Canyon Mountain south of John Day are of Triassic age (David Jones, oral commun., 1980).

The Permian rocks are overlain unconformably by Late Triassic sedimentary sequences of limestone, argillite, graywacke, and chert and intercalated layers of volcanic and volcanoclastic rocks (Dickinson and Vigrass, 1965; Brooks and Vallier, 1978). Contacts with Permian rocks are commonly tectonic; slices of Triassic rocks are in places folded and faulted into the Permian strata. The source rocks for the sediments were uplifted melange and volcanic rocks. Sedimentation into trenchlike basins associated with subduction continued to Early and Middle Jurassic time. Younger Jurassic volcanoclastic and sedimentary rocks rest unconformably on all older units.

METAVOLCANIC ROCKS

Metavolcanic rocks consisting of quartz keratophyres, keratophyres, spilite, keratophyric tuffs, and meta-andesite and some interbedded layers of chert, conglomerate, argillite, and marine limestone are widespread in northeastern Oregon across the Baker and Pine quadrangles according to Gilluly (1935, 1937). Gilluly named these rocks the Clover Creek Greenstone and noted that they extend westward from the Baker quadrangle as well as eastward and that similar rocks are exposed in the southern part of the Seven Devils Mountains in Idaho. According to Gilluly (1935), the spilites and keratophyres are albitized equivalents of submarine basalts and andesites; but the quartz keratophyres are likelier to be effusive equivalents of trondhjemitic magma, in composition similar to albite granite and albitized dacite and sodarhyolite. The evidence of albitization in these rocks is not as strong as in the less silicic rocks.

Hamilton (1963) recognized that these metavolcanic rocks, called the Seven Devils Group by Vallier (1974), are of island-arc type and pointed out that metamorphosed tuffs and agglomerates are more

abundant than are flows. Composition ranges from basaltic to rhyolitic; the intermediate rocks are most abundant. Marine fossils in interbedded metatuffs and metasediments in the Cuprum quadrangle southwest of Riggins, Idaho, indicate a Permian and Late Triassic age. In the Riggins quadrangle, the metavolcanic rocks are exposed under the Martin Bridge Limestone of Late Triassic age.

Tethyan fusulinids of late Guadalupian age (Bostwick and Nestell, 1967, p. 96) in pods of limestone surrounded by metavolcanic rocks 19 km east of Baker indicate Late Permian volcanism and contemporaneous sedimentation. Fusulinids from limestone lenses in sedimentary layers associated with metavolcanic rocks 6 km southeast of John Day are of Wolfcampian or Leonardian age (Thayer and Brown, 1964, p. 1255).

The volcanism in the Snake River Canyon and vicinity, the Wallowa Mountains, and Seven Devils Mountains is of Early Permian and Middle and Late Triassic age (Vallier and others, 1977; Brooks and Vallier, 1978). The Permian volcanic-arc rocks are quartz keratophyres, keratophyres, spilites, and volcanoclastic rocks mainly of andesitic composition. Conglomerate, sandstone, siltstone, and minor limestone are interbedded with volcanic rocks. The Permian rocks are overlain by Middle and Late Triassic volcanic-arc rocks consisting mainly of basalt, andesite, and dacite that have been metamorphosed to greenstones and spilited to spilite, keratophyres, and quartz keratophyres. The chemistry shows that all volcanic rocks, as well as trondhjemitic plutonic rocks, belong to potassium-poor calc-alkaline series typical of island arcs. In Idaho, the metavolcanic rocks continue north and northeast of Riggins and are exposed along the Salmon River south and north of White Bird (36 km north of Riggins) and along the South Fork of the Clearwater River near Harpster.

To compare the chemical composition of volcanic rocks in the Seven Devils Group (Hamilton, 1963; Vallier and Batiza, 1978) and Clover Creek Greenstone (Gilluly, 1937) with the late Paleozoic rocks in the northwestern Sierra Nevada (Hietanen, 1973a, 1977, 1981a), the available chemical analyses were plotted in ternary diagrams (fig. 2). The most striking difference, shown by diagrams 2A and 2B, is that the Seven Devils and Clover Creek rocks contain more alkalis and less calcium than the Paleozoic rocks in the northwestern Sierra Nevada. The Or-Ab-An (fig. 2C) diagram shows that the normative feldspar in the Oregon spilites and keratophyres is albitic, whereas in the Sierra Nevada area, the metabasalt and meta-andesite contain a considerable amount of normative anorthite produced by a high calcium content.

From this composition, abundant epidote minerals (Hietanen, 1974) crystallized in the low-grade rocks. These differences in composition and mineralogy, however, could have been produced by a later spilite reaction that was recognized by Gilluly (1935, 1937) and Hamilton (1963) to have been common in the metavolcanic rocks in eastern Oregon and western Idaho. The spilite reaction involves introduction of sodium and removal of calcium, resulting in albitization of plagioclase. The quartz content is generally higher in the Oregon rocks (fig. 2 D, E), probably because of loss of silicon during the metamorphism in the Sierra Nevada, as described by Hietanen (1973b, p. 2116; 1975).

The primary magmas and their differentiation products in Oregon and the Sierra Nevada were essentially similar, belonging to an island-arc-type calc-alkaline series. Gilluly (1935) pointed out that the silicic end members of the spilite-keratophyre-quartz keratophyre series are effusive equivalents of trondhjemitic, thus similar to the sodarhyolite in the Feather River area. As shown in figure 2, these silicic end members in Oregon (Nos. 6, 7, 8) plot close to the sodarhyolites in the Feather River area (Nos. 461, 1797) in the Q-Or-Ab, Q-F-M, and Alk-Fe-Mg diagrams, but an extremely An-poor feldspar content shown in the quartz keratophyres (Nos. 6, 7, 8) by the Or-Ab-An diagram suggests that even these silicic end members in Oregon were affected by albitization.

METAMORPHIC FACIES

Much of the Paleozoic rocks in eastern Oregon show only a slight deformation and minor recrystallization; in places, however, strong deformation, shearing, and thorough recrystallization have transformed the argillite into phyllite and schist, limestone into marble, and volcanic rocks into greenstones. The newly formed minerals, albite, muscovite, and chlorite with some epidote, calcite, and amphibole, indicate conditions of the greenschist facies during the recrystallization. Mineral assemblages typical of the amphibolite facies occur locally. Porphyritic textures and pyroclastic structures are easily recognizable in most of the greenstones. Only near some igneous masses was the recrystallization more thorough, as in the Riggins quadrangle (Hamilton, 1963), where metavolcanic rocks are strongly deformed and consist of albite, chlorite, epidote, actinolite, leucoxene, quartz, calcite, muscovite, magnetite, and hematite in varying proportions and combinations, thus mineralogically similar to the metavolcanic rocks in the Feather River area (Hietanen, 1973a, 1976, 1977). Locally, amphibolite-facies min-

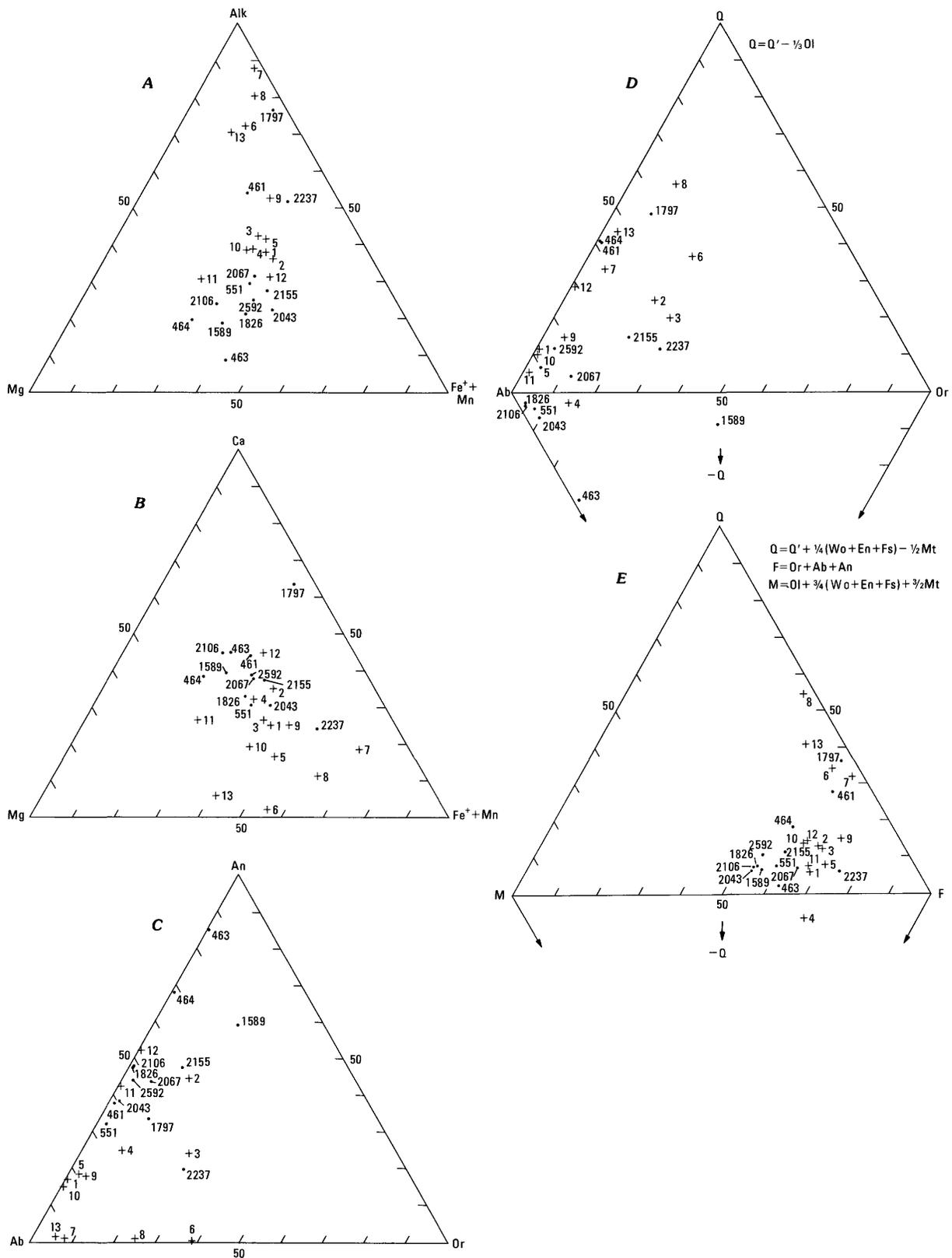


FIGURE 2.—Ternary diagrams showing composition of late Paleozoic metavolcanic rocks in northwestern Sierra Nevada (•) and eastern Oregon (+) in ionic percentages. A, Alkalies (Alk), magnesium (Mg), and total iron and manganese ($Fe^{total}+Mn$). B, Calcium (Ca), magnesium (Mg), and total iron + manganese ($Fe^{total}+Mn$). C, Normative orthoclase (Or), albite (Ab), and anorthite (An). D, Normative quartz minus 1/3 olivine (Q), orthoclase (Or), and albite (Ab). E, Normative quartz (Q), feldspar (F), and mafic minerals as orthosilicates (M). Nos. 2371, 2043, 2106, 2592, 1589, 2067, 2155, and 2237 refer to analyses in Hietanen (1981a); 551, 463, 464, and 461 are from Hietanen (1973a); 1826 and 1797 are from Hietanen (1977). Nos. 1, 2, and 3 refer to analyses of the Seven Devils Group (Hamilton, 1963, p. 8); 4, 5, 6, 7, and 8 to analyses of Clover Creek Greenstone (Guilluly, 1937, p. 25); 9, 10, 11, 12, and 13 to Permian volcanic rocks in Snake River Canyon (Vallier and Batiza, 1978) as follows: 9, an average of three intermediate compositions (anal. 6, 7, and 9 in table 2); 10, an average of two spilites (anal. 8 and 10); 11 and 12 are spilites; 13, an average of two quartz keratophyres (anal. 3 and 4 in table 2).

erals such as hornblende and garnet occur next to the igneous masses. A complete gradation from undeformed pillow lava to "glaucophane" schist was described by Thayer and Brown (1964) from rock near Pleasant Hill in the Mount Vernon quadrangle (13 km southwest of Baker). According to Swanson (1969), however, the amphibole in this rock is not glaucophane but blue-green hornblende.

The high-pressure-low-temperature mineral assemblages typical of trench melange occur in two localities in the Mitchell quadrangle, where they are associated with metasedimentary and metavolcanic rocks, or with serpentinite (Swanson, 1969; Hotz and others, 1977). Lawsonite and crossite occur locally with muscovite-chlorite schist that is tightly folded on northeast-trending axes.

STRUCTURES AND CORRELATION

Structural trends in the Paleozoic rocks in central and eastern Oregon are commonly to northeast. Exceptions occur in places as a result of local folding (G. W. Walker, oral commun., 1980) or faulting and brecciation before deposition in the John Day area of the Upper Triassic Begg Formation of Dickinson and Vigrass (1965), adopted as the Begg Member of the Vester Formation by Brown and Thayer (1977) and deposition of the Martin Bridge Limestone near the Oregon-Idaho border. Merriam and Berthiaume (1943) stated that the folding in the Grindstone and Twelvemile Creek area took place after the deposition of the Coyote Butte Formation, dated as Leonardian by Bostwick and Koch (1962), and before the Upper Triassic Begg Formation was laid down. Pre-Early Jurassic structures in Upper Triassic rocks shown by Dickinson and Thayer (1978) include accordion folding on south-plunging axes that implies a Late Triassic to Early Jurassic east-west shortening at the time of the eastward subduction of the Sierra Nevada-Klamath arc.

The melange terrane is thought by Dickinson and Thayer (1978) to be a product of subduction that lasted until at least mid-Triassic time. Sedimentation continued throughout the deformation into successive wedge-shaped minibasins formed within the subduction zone. The accretion of the melange and overlying Late Triassic and Early Jurassic shelf sediments onto the continent is thought to have resulted from arc-continent collision with subduction downward to the northwest.

In easternmost Oregon and west-central Idaho, northeast trends are prominent in the Permian metasedimentary and metavolcanic rocks, as shown on the geologic maps by Gilluly (1937), Pardee and others (1941), Prostka (1962, 1967), Vallier (1974), and

Hamilton (1969, pl. 3). The belt of melange consisting of Permian and Early Triassic ophiolitic blocks and fault slices overlain by oceanic metasedimentary and metavolcanic rocks (Elkhorn Ridge Argillite, Burnt River Schist) continues eastward to the Oregon-Idaho border and may continue into the Riggins region of western Idaho (Vallier and others, 1977; Brooks and Vallier, 1978). The contacts between the ophiolitic bodies and supracrustal rocks are tectonic; the style of deformation with northeast trends is well shown by scattered elongate limestone lenses. The range of known ages of supracrustal rocks, Pennsylvanian to Mesozoic, confirms that in this easternmost part of the belt, strong tectonic movements and sedimentation continued intermittently from late Paleozoic to Early Jurassic time.

The combination of long-lasting subduction and contemporaneous accumulation of sedimentary and volcanic material as suggested by Dickinson and Thayer (1978) for the John Day area is broadly similar to the sequence of events in the Klamath Mountains, where upper Paleozoic rocks were tectonized and subsequently incorporated into younger strata. In the Feather River area, northern Sierra Nevada, the recrystallization has destroyed most of the fossils, disallowing specific correlations. The ages of the igneous rocks and the structures and textures of the metavolcanic and metasedimentary sequences suggest a long duration of subduction and contemporaneous sedimentation and volcanism within the suture zone (Hietanen, 1981a, b), the accumulation lasting from Pennsylvanian to Late Triassic time and subduction continuing from middle Paleozoic to late Triassic and Jurassic time along the Melones fault zone on the east and until the Late Jurassic along the Big Bend fault zone on the west (table 1).

In the Feather River area, metasedimentary rocks (phyllite and metachert) on the marginal basin floor (the Pennsylvanian Calaveras Formation) are between the continental block and the island arc (the late Paleozoic and Triassic? Franklin Canyon Formation) and were deposited on the ocean floor before the island arc was formed. The trench melange (the Horseshoe Bend Formation) is on the west.

In the John Day inlier in eastern Oregon (Dickinson and Thayer, 1978), the correlative lithologic belts within the wide zone of melange are in the same order: the metasediments in the south were deposited on a marginal basin floor that was a remnant of the ocean floor trapped between the continental block in the southeast and the island arc in the northwest. The oldest sediments there were deposited before the beginning of Permian island-arc volcanism. The arc-related subduction zone, as represented by the blue-

schist belt near Mitchell, is on the northwest, which suggests subduction to the southeast toward the continent. Faulted blocks of ophiolite scattered throughout the melange terrane in Oregon suggest that all these units are now parts of a major tectonic suture system. Together with the arching trends, these structures suggest that the late Paleozoic to Middle Jurassic suture system extends from the western Sierra Nevada through the Klamath Mountains to eastern Oregon and western Idaho. The oldest metasedimentary rocks were deposited on the sea floor near the continent, and the island arc developed some distance from the continent as a result of subduction. In the Sierra Nevada and Klamath Mountains, the dip of the Benioff zone was to the east, that is, toward the continent, as is normal in the modern island-arc systems. The relations in Oregon suggest a similar tectonic setting.

TABLE 1.—*Correlation of geologic events within suture belt*

	Northwest Sierra Nevada	Klamath Mountains	Eastern Oregon
Plutonism	Cretaceous	Jurassic (165-167 m.y.)	Cretaceous
	Jurassic (162 m.y.)	Early Triassic	Jurassic
	Triassic	K-Ar age 246 m.y.	Late Triassic
Tectonism	Jurassic Permian to Triassic	Jurassic Triassic	Jurassic Permian to Triassic
	Devonian (in east)	Devonian	
Volcanism	Triassic(?) Permian Pennsylvanian	Jurassic Triassic Permian	Jurassic Late Triassic Permian
	Late Triassic Permian(?) Pennsylvanian	Early Jurassic Late Triassic Permian Devonian	Jurassic Late Triassic Permian Pennsylvanian Mississippian Devonian

Dickinson and Thayer (1978) point out that the Seven Devils volcanic arc was capped by platform limestone in Late Triassic time, and thus these arc rocks must have been emplaced earlier during plate movements in late Paleozoic to Early Triassic time that formed the melange within which these volcanic rocks could be encased. Their concept is in agreement with the idea advanced in this paper that the melange in eastern Oregon is an extension of the Sierra Nevada-Klamath suture system formed along the western and northwestern margin of the block (western and northwestern margin of the block (western Nevada and northeastern California) that was accreted to the continent during the Permian and Triassic Sonoma orogeny, as suggested by Davis, Monger, and Burchfiel (1978).

East of the Melones fault, the accreted block in-

cludes Paleozoic and early Mesozoic calc-alkaline volcanic rocks that are generally referred to as island-arc volcanic rocks. These rocks are underlain by the Silurian Shoo Fly Formation, the lower part of which is mainly continentally derived sandstone and blastoclastic quartzite accumulated on the continental shelf. The Paleozoic volcanic-arc rocks accumulated on the continental margin (Andean-type arc) as a result of subduction during which melange in the suture belt was formed. The Pacific floor and much of the sediments on it as well as much of the late Paleozoic island-arc rocks were subducted under the continental margin. The ultramafic slabs most likely flaked off from the subducting sea floor, forming, together with the overlying sedimentary and volcanic rocks, a chaotic mixture of melange in Oregon and in the Klamath Mountains and an imbricated melange in the northwestern Sierra Nevada. The early subduction in the Sierra Nevada and Klamath Mountains was along fault zones bordering the suture system on the east; later, in early Mesozoic time, subduction was along faults bordering it on the west. The zone of melange in eastern Oregon was formed in Early Triassic time and includes blocks of Permian island-arc rocks. This zone is correlative with the melange belts in the west in the time of its formation, in its lithology and structure, and presumably in its tectonic significance. All these belts are marginal to the same Paleozoic block that was accreted to the North American continent during the Sonoma orogeny.

Davis, Monger, and Burchfiel (1978) recognize three accreted Mesozoic belts in the western Cordillera. The oldest of these was emplaced in Late Triassic time and includes the Elkhorn Ridge Argillite, Burnt River Schist, and Canyon Mountain Complex in Oregon, some Paleozoic rocks in the eastern Klamath Mountains, and Calaveras-type rocks in the western Sierra Nevada. A younger belt, accreted from Early to late Jurassic time, includes the western Paleozoic and Triassic belt in the Klamath Mountains and parts of the so-called Calaveras Formation in the western Sierra Nevada. The youngest belt was accreted in Cretaceous time and includes Late Jurassic and Cretaceous rocks.

An exotic origin for some Permian rocks in the oldest belt in British Columbia and Washington and in the Seven Devils Mountains, Idaho, has been suggested by several workers (Jones and others, 1978; Davis and others, 1978) on the basis of Tethyan fusulinids (Danner, 1976; Davis and others, 1978) and paleomagnetism. Similarity of the fusulinids to those in Japan supports a concept that the entire Paleozoic Pacific floor was subducted under the North Ameri-

can plate during Paleozoic and Mesozoic time. A tropical aspect of the Permian fauna and paleomagnetism in some volcanic-arc rocks in British Columbia and Washington and in the Seven Devils Mountains suggest that these rocks originated near the Permian and Triassic equator and were brought to their present location by northward drifting and rotation (J. W. Hillhouse, oral commun., 1980). The northward drifting and contemporaneous eastward subduction could have been components of an oblique subduction of the Pacific lithosphere under the North American continent.

SUMMARY OF STRUCTURES; CUSP IN PERMIAN ARCS

The prevalent structural trends in Permian rocks in eastern Oregon are consistently to the northeast. These trends, together with the nature of the lithologic units, major faults, and zones of melange, support the concept that a continuous major structural zone, a late Paleozoic and early Mesozoic suture system, arches from the western Sierra Nevada through the Klamath Mountains to eastern Oregon and west-central Idaho. Remnants of late Paleozoic and early Mesozoic island-arc rocks are easily recognized in this Sierra Nevada-Klamath-Oregon-Idaho arc which formed west and northwest of the Paleozoic block (in western Nevada and northeastern California) that accreted to the North American continent in Permian and (or) Triassic time. The trench related to this arc, now a zone of melange west and northwest of the island-arc rocks, lay seaward of the arc. Remnants of sediments deposited on the sea floor that later became a marginal basin floor are preserved between the Paleozoic continental block and the island-arc rocks. Island-arc rocks west and northwest of the late Paleozoic and early Mesozoic trench melange are components of a second arc, either local (Late Jurassic in California) or exotic in origin (Seven Devils Group in Oregon and Idaho).

Northwest of the Idaho batholith, the northeast trends of the suture system in eastern Oregon meet the northwest-trending structures that curve from British Columbia through Washington to Idaho. Two sets of lineations and fold axes occur where these structures meet (Hietanen, 1961). One set, which in places seems older, parallels the northeast trends of the southern arc; the second set parallels the northwest trends of the northern arc. These structures do not loop around, but rather seem to form a cusp that was only locally obscured by an overprint of younger structures and modified by the Cretaceous Idaho batholith.

Similar cusps occur in modern island-arc systems formed on ocean basins where no horizontal shear

component is involved (Wilson, 1968). In Oregon and Idaho, the cusp could have formed during the collision of plates, the arcuate shape reflecting the margin of the block accreted to the North American plate in Paleozoic time.

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