Geology of the Pulga and Bucks Lake Quadrangles, Butte and Plumas Counties, California

GEOLOGICAL SURVEY PROFESSIONAL PAPER 731

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By ANNA HIETANEN

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A petrologic and structural study of metamorphic and plutonic rocks

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GEOLOGY OF THE PULGA AND BUCKS LAKE QUADRANGLES, BUTTE AND PLUMAS COUNTIES, CALIFORNIA

By ANNA HIETANEN

ABSTRACT

The area studied is at the north end of the western metamorphic belt of the Sierra Nevada. Structurally it is in the inner belt of the Nevadan arcuate segment, in which northerly trends of the central Sierra Nevada turn to the northwest and locally even to the west. The northeast part of the area is traversed by a major northwest-trending fault zone, the Melones fault, and an adjoining serpentine belt. Orthoquartzite and interbedded phyllite northeast of this belt are continuous with the Shoo Fly Formation of probable Silurian age in the neighboring areas to the north and east. Correlation of the metasedimentary and metavolcanic rocks southwest of the Melones fault is uncertain because strong deformation and recrystallization have destroyed the fossils beyond positive identification. On lithologic grounds and assuming a widespread volcanic activity, the pyroclastic sequence is tentatively correlated with Paleozoic pyroclastic formations in the south and with those dated on the basis of fossil evidence as Devonian and Permian in the neighboring Taylorsville area in the east. Fault contacts occur between the metasedimentary and the pyroclastic rocks in most of the area, but in the central part, where trends turn to the west, and also in the northwestern part, some contacts are not faulted but folded.

Two sets of folds are apparent on good outcrops of distinctly bedded parts of the metamorphic rocks. The major folds trend northwest; the axial plane foliation is either vertical or dips 70°–85° NE. (more rarely to the southwest). The early structures were modified by Late Jurassic and Early Cretaceous plutons that shouldered the wallrocks aside during emplacement and caused a second episode of deformation and recrystallization of the wallrocks to the epidote-amphibolite facies. The second deformation appears as a strong steeply plunging lineation that in places is the axis of folding.

Two groups of intrusive rocks have invaded the metamorphic sequences. The older of these ranges from hornblendite and hornblende gabbro to hornblende quartz diorite and trondhjemite in composition. It represents deep-seated and hypabyssal equivalents of the metavolcanic rocks and is about the same age or only a little younger than the metavolcanic rocks. The younger intrusive group forms round plutons, 3–13 miles in diameter, that range from pyroxene diorite to monzotonalite in composition. Potassium-argon ratios in hornblendes and biotites in these rocks have yielded ages ranging from 143 to 128 million years.

Most of the plutons are normally zoned: their border zones consist of hornblende-biotite quartz diorite, and the central parts consist of monzotonalite. The Bucks Lake pluton, however, has an older central mass of pyroxene diorite that is partly brecciated and altered to hornblende-bearing rock along its borders. Chemical composition and trace-element content, together with the structural relations, suggest that the pyroxene diorite is an early differentiate of the same magma from which the hornblende quartz diorite crystallized. Biotite-epidote tonalite forms one large and several small bodies in the southern part of the Bucks Lake quadrangle. Chemically these are similar to the quartz diorite-monzotonalite plutons; the differences in mineralogy result from a higher water content in the magma. The most silicic differentiates associated with the biotite-rich tonalites have trondhjemitic affinities.

Tertiary volcanic rocks are widespread in the eastern and northwestern parts of the area. The lowermost flows are black basalt that is tentatively correlated with Durrell's Lovejoy Formation. The overlying pyroclastic andesite is probably equivalent to Durrell's Penman Formation of Pliocene age. Augite basalt on top of Mount Ararat and small pluglike bodies of olivine basalt in the southern part of the Bucks Lake quadrangle may be equivalent to similar basalt in the Blairsden quadrangle, which basalt was correlated with Russell's Warner Basalt of Pliocene age by Durrell.

INTRODUCTION

The Bucks Lake quadrangle and the adjoining Pulga quadrangle are at the north end of the Sierra Nevada gold belt. They cover an area of 458 square miles bounded by lat 39°45′ and 40°00′ N. and long 121°00′ and 121°30′ W. (fig. 1). A narrow strip along the north boundary of these quadrangles was also mapped in order to trace the contacts of the granitic plutons. The area is deeply dissected by canyons of the North Fork and the Middle Fork of the Feather River and their tributaries. The highest mountains near Bucks Lake rise 5,000 feet above the canyon of the North Fork, to an elevation of 7,000 feet above sea level. The high plateau to the southeast and northwest is 3,000 feet above the river canyons, at an elevation of 5,000–6,000 feet above sea level.

The area is timbered by pines, fir, incense cedar, and oak. Many slopes are covered by thick growth of manzanita and mountain laurel. In addition to the roads shown on the maps (pls. 1, 2), many logging roads and trails traverse the area. Exposures are excellent along the rivers and large creeks as well as on the highest elevation near Bucks Lake and in the northernmost part

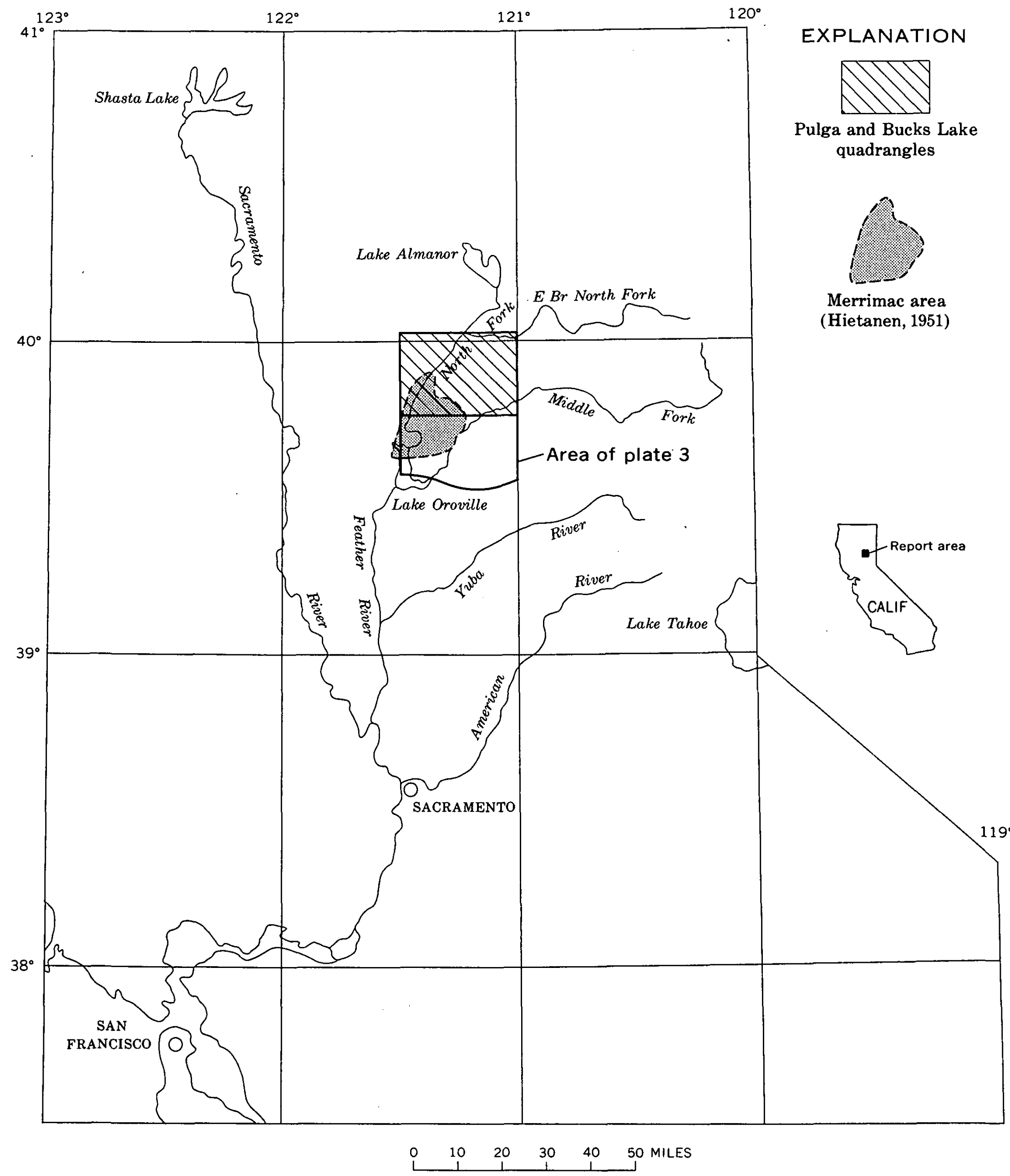


FIGURE 1.—Location of area studied, northern California.

of the Pulga quadrangle, but they are few and small on many slopes and on level ridges of the high plateau.

PREVIOUS WORK

The Bucks Lake and Pulga quadrangles make up the north half of the old Bidwell Bar quadrangle mapped by Turner (1898). The metavolcanic rocks were shown as amphibolite on that map. Turner included the metasedimentary rocks in the Calaveras Formation, which he considered to be Carboniferous on the basis of stratigraphic continuity in adjacent areas and on the fossil evidence. Fossils that were considered to indicate a Carboniferous age were found in limestone near Spanish Creek in the eastern part of the Bucks Lake quadrangle, and on the slope west of Onion Valley Creek, 3½ miles southeast of the mouth of this creek in the southeast corner of the Bucks Lake quadrangle. Rounded crinoid stems and tests of Foraminifera were found in the Diadem lode at Edmanton on the south side of Eagle Gulch (sec. 28, T. 24 N., R. 8 E.). A small area of metasedimentary rocks in the northeastern part of the Bucks Lake quadrangle was shown as the Cedar Formation of "Jura-Trias" age.

The southern part of the Pulga quadrangle was included in the description of the Merrimac area by Hietanen (1951). On the geologic map accompanying that report, the subdivision of the metamorphic rocks was partly genetic and partly based on the mineral assemblages found in the rocks.

The geologic map of California by Burnett and Jennings (1962) shows metasedimentary rocks of Paleozoic age and metavolcanic rocks of Jurassic and Triassic age, both undivided. Serpentine and other ultramafic intrusive rocks are shown as Mesozoic in age, and the granitic plutons as younger Mesozoic. The small area of Turner's (1898) "Jura-Trias" Cedar Formation is shown as Triassic marine. The Triassic age of these rocks in the area north of the Bucks Lake quadrangle has been verified by McMath (1958) on the basis of fossils that he found.

The metasedimentary rocks in the extreme northeast corner of the Bucks Lake quadrangle were included in the Shoo Fly Formation of probable Silurian age by Clark, Imlay, McMath, and Silberling (1962) and by McMath (1966). The Silurian age for at least part of the rocks included in the Shoo Fly Formation by these authors was suggested by correlating the rocks with the fossiliferous Silurian Taylorsville Formation farther northeast. Paleozoic stratigraphy in the Taylorsville area was set up by Diller (1908). Later work, however, showed that a part of the sequence that he considered normal is overturned. The first irrefutable proof of this was given by Durrell and Proctor (1948, p. 171), who found that a metarhyolite sequence, the Sierra Buttes Formation of McMath (1966), overlies the Shoo Fly Formation with angular unconformity south of Taylorsville. Revision of stratigraphy in the Taylorsville area is given by McMath (1966, p. 176–178). In this area the Taylorsville thrust separates the overturned sequence of the upper plate from the normal sequence of the lower plate, and both plates include the Shoo Fly and Sierra Buttes Formations (McMath, 1958, 1966).

Creely (1965) found tetracorals of late Paleozoic age, probably Permian, in the limestone interbedded with supposed Calaveras slates in the northwestern part of the Oroville quadrangle, which joins the Pulga quadrangle in the southwest. The fossil locality is in the western continuation of the metasedimentary formation exposed in the southwest corner of plate 3 of this report, just north of lat 39°40′ N. and 4 miles to the west.

PURPOSE AND SCOPE

The short summary of previous work shows that very little is known about the stratigraphy, age, and metamorphism of the pre-Cretaceous rocks of the area. The earlier stratigraphy (Turner, 1898) combined all metasedimentary rocks under the name Calaveras, to which a Carboniferous age was assigned on the basis of fossil evidence that is not considered to be conclusive by modern standards. Because no new identifiable fossils were found during this work, an attempt has been made to work out a stratigraphic sequence and correlate the mappable rock units with the known formations in the neighboring areas. This tentative correlation is based on lithology and on the stratigraphic position of the units.

The stratigraphy and lithologic correlation are complicated by profound deformation and recrystallization that have destroyed most of the primary structures, such as possibe crossbedding, ripple marks, and channeling, that would help in determining whether the strata are right-side-up or overturned. The bedding is preserved in some of the metasedimentary rocks, such as metachert, but in most of the phyllite the only measurable structural element is foliation. The stratigraphy can then be worked out only by mapping the distribution of the rock units.

The stratigraphy is further complicated by faults that divide the area into northwest-trending belts. Each belt seems to have a different lithology, making the correlation across the faults uncertain if not impossible. Comparison of metamorphic and structural history of the individual belts may throw some light on the problem of a possible large age difference between them, such as was suggested on the earlier geologic maps.

The Late Jurassic and Early Cretaceous plutons have modified or destroyed the earlier structures around them, so that these structures can be studied only in rather small parts of the area.

The occurrence of metamorphosed sodarhyolite as the silicic end member of the meta-andesite–metadacite sequence in the eastern part of the area is an intriguing problem in itself. Potassium-rich metarhyolite, probably not much different in age, is associated with metabasalt in the western part of the same belt. Petrologic study of all these rocks should help in solving the problem of this difference in the potassium content of the metarhylolites.

Another problem in the area is the "reversed" zoning in one of the plutons. Most of the plutons are normally zoned, the basic border zones grading to silicic centers, but in the Bucks Lake pluton the most basic differentiate occurs in the central part and seems to grade to silicic hornblende quartz diorite at the borders. Petrologic study of the plutonic rocks helps solve this problem.

This work also contributes to the knowledge of the ultramafic rocks and their serpentinization in the Sierra Nevada and of the pressure and temperature conditions during the metamorphism and plutonism.

STRUCTURAL SETTING

The area lies in the inner zone of an arcuate segment of a tightly folded Nevadan orogenic belt (pl. 3). The regional trends south of the area are southward, and in the central part of the Pulga quadrangle they are westward. Faults divide the area into four belts; rocks of one or two formations are exposed in each belt. Structural relations suggest that generally the younger formations are in the successive belts to the southwest (fig. 1). The rocks are isoclinally folded, and in most parts of the area folds are overturned to the southwest. The faults seem to be high-angle faults, but overthrusting to the southwest—or rather underthrusting in a subduction zone, to the northeast—cannot be ruled out. Late Jurassic and Early Cretaceous plutons modified the structures by shouldering the wallrocks aside and causing a second episode of deformation and recrystallization. On the maps (pls. 1, 2) this is clearly demonstrated as the curvature of the trends of the metamorphic wallrocks around the plutons.

A major belt of ultramafic rocks bordered by the Melones and Rich Bar faults crosses the northeastern part of the area. In the south, elongate bodies of ultramafic rocks, partly altered to serpentine and talc schist, occur along the fault contacts between the formations. In the central part of the arcuate segment they thicken in places of tectonic low pressure. The ultramafic bodies were deformed and recrystallized during the major period of deformation and recrystallization, indicating that the faults they intruded started to form early. Breccia zones as much as several meters wide along the major faults are evidence of continued movement after the recrystallization. Thus, each fault block forms a unit, making the correlation across the faults uncertain.

ROCKS OF THE AREA

The Melones fault, accompanied by a belt of serpentine, divides the area into two parts that have different lithologies. The rocks northeast of the Melones fault are continuous with the Shoo Fly Formation of Clark, Imlay, McMath, and Silberling (1962) and of McMath (1966) in the adjoining areas. The rocks southwest of the Melones fault are divisible into four mappable units that differ strikingly in their lithology. These are called the Calaveras, Franklin Canyon, Duffey Dome, and Horseshoe Bend Formations.

The name Calaveras Formation was applied by Turner (1898) to all metasedimentary rocks in the Bidwell Bar quadrangle. In this report the name Calaveras is restricted to the belt of metasedimentary rocks that in the Bucks Lake quadrangle lies immediately southwest of the Rich Bar fault and continues westward to the northern part of the Pulga quadrangle. This formation is believed to be the oldest of the four units southwest of the Melones fault. No new evidence indicating the age was found.

The name Franklin Canyon Formation is coined for a sequence of potassium-poor metavolcanic rocks that range in composition from meta-andesite through metadacite to metasodarhyolite and contain interbedded layers of metatuff of the same compositions. The main belt of these rocks is in the Bucks Lake quadrangle southwest of the Calaveras Formation. Similar rocks, probably also belonging to the Franklin Canyon Formation, lie unconformably on the Calaveras Formation in the northern part of the Bucks Lake quadrangle; this relation suggests that the Franklin Canyon Formation is the younger of the two. A continuous section through this formation is exposed in the deep gorge called Franklin Canyon on the Middle Fork of the Feather River (pl. 2).

In the central part of the Pulga quadrangle, the metavolcanic sequence that overlies the Calaveras Formation consists of metabasalt and of metarhyolite rich in potassium feldspar. This sequence is well exposed near Duffey Dome, after which it is named. Its age relation to the Franklin Canyon Formation is uncertain because igneous rocks and Quaternary deposits separate the exposures of the two formations. Together they form the major part of the metavolcanic sequence.

A succession of metamorphic rocks along Marble Creek and to the southeast in the vicinity of Deer Park in the Horseshoe Bend of the Little North Fork of the Feather River is very heterogeneous. It is composed of thin layers and lenticular bodies of quartzite, mica schist and phyllite, limestone, metabasalt, meta-andesite, metadacite, metarhyolite, and metatuff, all interbedded and isoclinally folded. This succession is called the Horseshoe Bend Formation. The metamorphic rocks west of the Merrimac pluton are most likely a part of this formation.

Two groups of igneous rocks are distinguished: (1) the older metamorphosed series in small to large bodies and ranging in composition from serpentine and pyroxenite through gabbro and quartz diorite to tonalite and trondhjemite and (2) the younger series that forms large plutons consisting of pyroxene diorite, hornblende quartz diorite, tonalite, and monzotonalite. These plutons are the northernmost exposed plutons in the western metamorphic belt of the Sierra Nevada and are comparable in their age and composition to the older plutons in the western part of the central Sierra Nevada (Bateman and Eaton, 1967, p. 1409).

Parts of the Bucks Lake quadrangle and of the northern Pulga quadrangle are covered by Tertiary basalt and pyroclastic andesite. Gravel deposits under these volcanic rocks have been mined for gold, as have some of the Quaternary lake deposits.

METASEDIMENTARY FORMATIONS

SHOO FLY FORMATION

ROCK UNITS

The rocks shown as a part of the Silurian(?) Shoo Fly Formation by Clark, Imlay, McMath, and Silberling (1962) and by McMath (1966) are exposed near Snake Lake and on both sides of Spanish Creek in the northeastern part of the Bucks Lake quadrangle. These two exposed parts of the Shoo Fly Formation are separated by Quaternary gravel deposits. The major rock type northwest of Snake Lake is a blastoclastic muscovite quartzite, orthoquartzite, that is weakly deformed. On the west this quartzite lies conformably on muscovite-chlorite phyllite. The outcrops south of the gravel near Spanish Creek consist of isoclinally folded mica schist that includes some thin layers of quartzite, metagraywacke, and interbedded limestone in which Turner (1898) reported fossils of Carboniferous age. Shearing stronger than that in the orthoquartzite is evident in the schist on Spanish Creek. A small isolated outcrop of orthoquartzite on Whitlock ravine (loc. 693) is the only occurrence of orthoquartzite south of the gravel. The strike and dip of bedding in this outcrop suggest that it may be interlayered and folded with the schist.

The contact between the orthoquartzite and the phyllite exposed under it is gradational over a few meters. The gradational rock is micaceous foliated quartzite in which the number and size of the quartz grains decrease toward lower beds. A layer of orthoquartzite is interbedded with the phyllite at locality 292 on Pineleaf Road. Layers of white granular quartzite overlie the orthoquartzite and are interbedded with it.

Two layers of limestone, interbedded with the phyllite, extend from Spanish Creek to Rock Creek and a short distance beyond. Both layers are 30–50 meters thick and contain micaceous material in addition to rather pure carbonate beds. Discontinuous thin layers and lenses of carbonate occur in the underlying shaly beds.

Metatuff, metarhyolite, and metadacite occur in two small synclinal areas within the schist south of Spanish Creek. These metavolcanic rocks probably are a part of the Shoo Fly Formation since the phyllite exposed under them is a lower part of the Shoo Fly Formation. Mineralogy of these metavolcanic rocks is similar to that of the corresponding rock types in the Franklin Canyon Formation.

PETROGRAPHIC DESCRIPTION

PHYLLITE AND INTERBEDDED QUARTZITE

The phyllite of the Shoo Fly Formation is fine grained and varies from light beige to brownish gray or dark gray, depending on the micaceous minerals present and on the amount of magnetite and hematite. Dark-gray to black slaty layers on the East Branch of Rock Creek at the east border of the Bucks Lake quadrangle are rich in carbon. In the northernmost part of the quadrangle, very fine grained light-tan muscovite phyllite is interbedded with muscovite-chlorite phyllite. In addition to muscovite and chlorite, biotite is common near Spanish Creek and to the south. Dark- to medium-gray layers rich in quartz are interbedded with phyllite. The thickness of these quartzitic layers ranges from a few centimeters to several meters; the thicker layers contain micaceous laminae. Some layers along Spanish Creek near the mouth of Whitlock Creek contain large round grains of albite that may constitute as much as 10 percent of the rock.

Thin sections of the phyllite show that chlorite is interleaved with muscovite, and both are parallel to the foliation. Chlorite is very pale green with bluish-gray interference colors. Biotite is reddish brown and strongly pleochroic. In many layers, flakes of biotite transect the wrinkled foliation, which is paralleled by muscovite and chlorite. Biotite is thus clearly younger than the other micaceous minerals. In some specimens helicitic inclusions of magnetite, sphene, and epidote mark the plane of foliation within the biotite flakes (for example, loc. 695, fig. 2).

Stilpnomelane (identified by X-ray pattern) occurs instead of biotite in some layers east of the mouth of Slate Creek (loc. 16). This mineral is found in reddish-brown slender flakes that either parallel the foliation or form radial clusters. The index of refraction, γ, is 1.686 ± 0.002.

Albite grains are 1–2 millimeters in diameter and contain rows of inclusions of epidote and sphene. In most grains these inclusions are helicitic, continuing from the albite to the surrounding micaceous minerals (fig. 2). This indicates that albite is not a relict clastic grain but that it was crystallized late during the same episode as the biotite.

Sphene, ilmenite-magnetite, magnetite, and hematite are common accessory minerals. Sphene occurs in tiny euhedral crystals and larger anhedral grains. Much of the magnetite is altered to hematite.

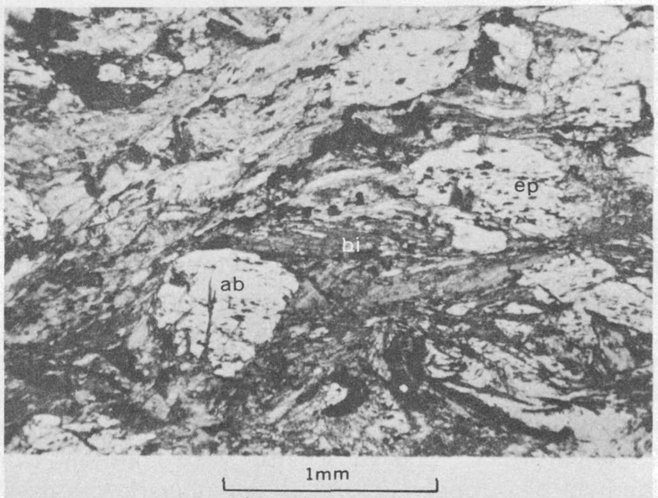


FIGURE 2.—Photomicrograph of helicitic inclusions of epidote (ep) in late biotite (bi) and albite (ab). The rows of inclusions are parallel to the external foliation. Biotite phyllite of the Shoo Fly Formation from the mouth of Whitlock Creek (loc. 695). Crossed nicols.

Garnet was found only in one specimen studied (loc. 16). Crystals are euhedral and only about 0.005 mm in diameter. Some are clearly zoned; the centers have n=1.783±0.002, and the rims n=1.782±0.002.

Quartzitic layers, foliated and wrinkled, consist of 70–95 percent quartz, 5–20 percent muscovite, and some biotite, magnetite, hematite, and sphene. In the foliated layers, the quartz grains (0.05–0.5 mm long) are elongated parallel to the foliation. In the wrinkled layers, the quartz grains are rounded or polygonal with sutured borders. Undulatory extinction is common in all quartz. Most of the muscovite is between the quartz grains, but some flakes transect the grain boundaries or are included in quartz. A few grains of albite and potassium feldspar occur in some layers.

ORTHOQUARTZITE

The orthoquartzite is light gray, rarely brownish gray, and thick bedded; blastoclastic coarse-grained layers, from 20 centimeters to several meters thick, are separated by thin (5–50 cm) schistose layers that contain more muscovite.

The coarse-grained layers consist of bluish-gray clear round grains of quartz embedded in a fine-grained matrix of muscovite and quartz. Most grains of quartz are 1–3 mm in diameter; some larger grains are scattered in light-gray sandstone west of Snake Lake. A few of the large grains of quartz are subhedral, but most are well rounded and nearly spherical; very few are elongate. Their color and translucency resemble phenocrysts in quartz porphyry or coarse-grained metarhyolite.

Thin sections show that the rounded grains of quartz make up about 90 percent of the orthoquartzite. Muscovite in tiny flakes and some small quartz grains are interstitial (fig. 3). Quartz grains show only very weak strain shadows and include tiny grains of magnetite, most of which are parallel to healed fractures. In the micaceous layers interbedded with the orthoquartzite, quartz grains are elongate and less than 1 mm long. They constitute about 30 percent of the rock, whereas the sericite-rich matrix makes up 70 percent. The matrix also contains tiny grains of quartz and albite, as well as some magnetite and hematite.

Very fine grained muscovite slate and fine-grained white granular quartzite overlie the orthoquartzite on the ridge north of Snake Lake. Micaceous laminae separate the individual beds of quartzite, which are 2–20 cm thick. The muscovite slate contains thin laminae of strongly deformed granoblastic grains of quartz. The magnitude of elongation and deformation of quartz seems to depend on the amount of muscovite: the layers rich in moscovite are more strongly sheared than the quartz-rich layers.

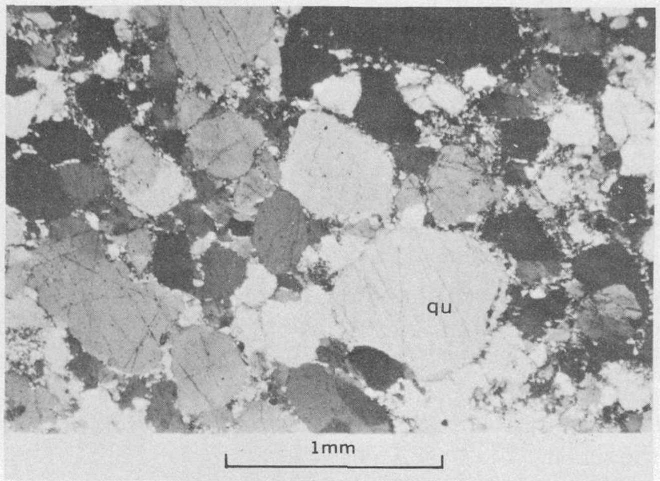


FIGURE 3.—Photomicrograph of orthoquartzite from the Shoo Fly Formation. Smith Lake (loc. 373). Matrix between the round grains of quartz (qu) consists of muscovite and quartz.

LIMESTONE

Most of the limestone is medium grained and light to medium gray; individual beds range from a few centimeters to a meter or more in thickness. A part of the southern unit on Rock Creek, however, consists of thin-bedded brown and white limestone in which white carbonate layers, 2–4 cm thick, alternate with brown micaceous layers of the same thickness. Carbonate-rich phyllite occurs as a gradational rock between the limestone and muscovite-biotite phyllite.

Recrystallization of limestone has destroyed the fossils beyond positive identification. Textures suggestive of fossil remains were observed in some thin sections of gray limestone on the north side of Spanish Creek.

STRUCTURE

Only a few structural features seen on the outcrops are described here because the Shoo Fly Formation covers too small an area for an extensive structural analysis. A complex isoclinal anticlinorium is exposed north of the Bucks Lake quadrangle (Moores, 1970).

Bedding (s_1) is well preserved in orthoquartzite where fine-grained micaceous layers are interbedded with coarser grained quartz-rich rock. Bedding can be observed in the phyllite only where thin quartzitic layers alternate with micaceous layers. In most of the homogeneous phyllite, bedding cannot be distinguished, and the foliation (s_2) is then the only measurable structure. In a few outcrops of phyllite, however, the bedding is evident because of variations in color, grain size, or the amount of micaceous minerals. Strong folding was observed in some outcrops. In these the foliation is parallel to the axial planes; it transects the bedding at the crests of folds and parallels the bedding on the flanks.

The major fold axes trend northwestward, and the rock units are strongly elongated in the same direction, as shown on plate 2. Northeast-dipping bedding, axial plane foliation, and northeast-plunging lineation are common and suggest overturning to the southwest. Indeed, folds overturned to the southwest are exposed on the roadcuts north of the quadrangle. Small second folds with northeast-plunging axes that parallel lineation are common in the phyllite south of Slate Creek.

CALAVERAS FORMATION

DISTRIBUTION AND THICKNESS

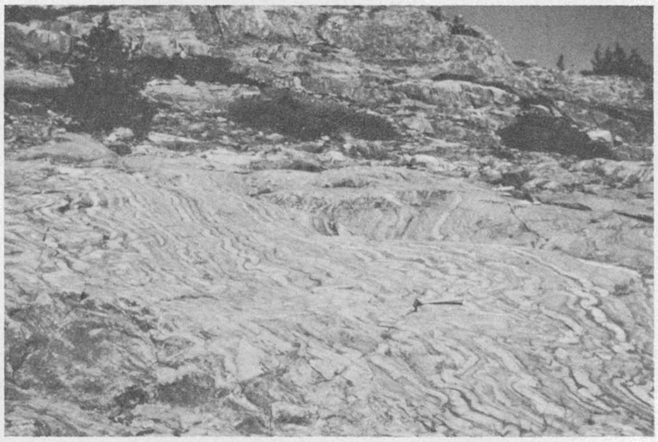
The major belt of metasedimentary rocks of the Calaveras Formation—interbedded metachert, phyllite, and some discontinuous limestone beds—traverses the mapped area in a northwesterly direction. The Bucks Lake and Oliver Lake plutons were emplaced into this belt and divide it into two branches. The southwest branch extends continuously from the southeast corner of the Bucks Lake quadrangle to the south side of Bucks Lake, where it borders the Bucks Lake pluton and then thins out between this and the Grizzly pluton. The northeast branch extends from the east border of the Bucks Lake quadrangle toward the northwest, forming the wallrocks of the Bucks Lake pluton in the north and enveloping the Oliver Lake pluton. From there this branch continues westward. It is partly covered by Tertiary basalts north of Grizzly pluton, but is well exposed again on the west side of the pluton. The west branch is only 1/2–1 mile wide and is terminated by a fault and metaigneous rocks near Rag Dump. The relation between the bedding and the cleavage together with the southward plunge of the fold axes in this western part of the belt suggest that the beds are younger toward the south, where some volcanic material is interbedded.

The thickness of the rock units vary. In the northern part of the Bucks Lake quadrangle layers of metachert about 100 m thick are interbedded with layers of phyllite of about the same thickness. In the southeastern part of the major layer of metachert is 200–500 m thick; several other layers that are only 5–20 m thick are not shown on the map (pl. 2). The thickness of most of the phyllite is difficult if not impossible to estimate because of isoclinal folding and well-developed axial plane foliation that has obscured the bedding. The total exposed thickness of the formation in the northern part of the Bucks Lake quadrangle is 1,500–2,000 m. The total thickness on the Middle Fork of the Feather River may be greater because phyllite is the major rock type there.

PETROGRAPHIC DESCRIPTION

METACHERT

The best exposures of metachert are in the northern part of the area. The glaciated outcrops near Campbell Lake and east of Long Lake (fig. 4) in the Pulga quadrangle and the ridges in the northwest corner of the Bucks Lake quadrangle provide many continuous sec-



A

B

FIGURE 4.—Structures and compositional variations in metachert of the Calaveras Formation. *A*, Glaciated outcrops east of Long Lake in the northern part of the Pulga quadrangle. Thin laminae of micaceous quartzite separate the beds consisting of 95-100 percent quartz. *B*, Detail of outcrop shown in *A*. The light-colored layers consist of quartz and are separated by thin micaceous layers.

tions of typical parts of the Calaveras Formation.

The metachert is thin bedded. Light- to medium-gray, rarely dark-gray, beds (3–8 cm thick) consisting of 95–100 percent quartz are separated by dark-brownish-gray micaceous layers (2–3 cm thick) and laminae (1–3 mm thick) in which muscovite and biotite are the common micaceous minerals. Locally chlorite instead of biotite occurs with muscovite; tremolite was seen in a few thin sections. Magnetite is a common accessory mineral.

The layers consisting almost exclusively of quartz are crisscrossed by thin veinlets of quartz. The grains in these veinlets are 0.05–0.5 mm in size, whereas those in the host rock are 0.01–0.03 mm in size. The grain size generally increases toward the plutons by recrystallization. Locally along the contacts part of the micaceous minerals, muscovite and biotite, are segregated into discontinuous laminae parallel to the cleavage that intersects the bedding. The color of the quartzitic layers changes from dark bluish gray through medium gray to very light gray with more thorough recrystallization. In the dark-bluish-gray metachert the magnetite is disseminated, whereas in the more thoroughly recrystallized layers, larger grains of magnetite are common. In a zone 200–500 m wide next to the plutons, the metachert is recrystallized to medium-grained white- to light-gray granular quartzite still preserving its thin-bedded structure. The common grain size in this quartzite is 0.1–0.3 mm for quartz and 0.1–1.5 mm for micaceous minerals.

FIGURE 5.—Porphyroblasts of cordierite in biotite-anthophyllite schist of the Calaveras Formation near the northwestern contact of Grizzly pluton (loc. 930).

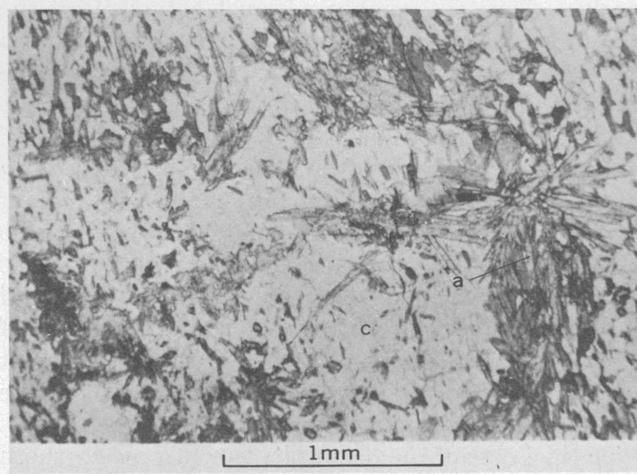


FIGURE 6.—Photomicrograph of the rock shown in figure 5. Anthophyllite (a) prisms are clustered around cordierite (c) porphyroblasts. Ordinary light.

PHYLLITE

The phyllite of the Calaveras Formation is well to moderately foliated, medium to dark gray, fine grained, and consists mainly of quartz (40–90 percent), muscovite, biotite and (or) chlorite. Albite (1–5 percent) occurs with quartz in some thin layers. Numerous garnet crystals 3–4 mm long occur in biotite phyllite east of the Oliver Lake pluton; elsewhere garnet is rare. Magnetite, hematite, pyrite, sphene, rutile, and tourmaline are the common accessory minerals; abundant graphite and (or) magnetite are disseminated through some layers. In many localities near the plutons, cordierite, andalusite, and staurolite crystallized as porphyroblasts that are larger than the other mineral grains. Cordierite is the most common of these; it occurs either with biotite and andalusite—as in the southern part of the Bucks Lake quadrangle—or with anthophyllite. Sillimanite crystallized with andalusite and cordierite in biotite phyllite just south of the Bucks Lake pluton. Large porphyroblasts of cordierite (½–2 cm long, figs. 5, 6) and prisms of anthophyllite abound in many layers of phyllite north and northeast of Grizzly pluton near the northern border of the Pulga quadrangle. Cordierite also occurs in many micaceous layers of metachert at Chambers Peak and elsewhere near the contacts of the plutons. Pseudomorphs of micaceous minerals after staurolite occur in muscovite-biotite phyllite exposed in the west-central part of the area south of the Bucks Lake pluton.

Quartz grains are polygonal or elongate and 0.01–1 mm long. The common size in the lepidoblastic micaceous layers is 0.01–0.03 mm, and in the interbedded quartz-rich layers and laminae, 0.03–0.3 mm. In small clusters and veinlike bodies the quartz grains are somewhat larger, usually 0.3–1 mm long. Toward the plutons and locally elsewhere, grain size grows larger with higher degree of recrystallization.

Muscovite is the major micaceous mineral in most of the phyllite. It occurs in minute interstitial flakes

(0.01–0.5 mm long) or is segregated as larger flakes in thin laminae parallel to the foliation.

Biotite is interleaved with muscovite, or it forms larger flakes that intersect the plane of foliation and thus postdate it. In many layers near the plutons, and particularly in the andalusite-staurolite schist, biotite is the sole micaceous mineral. The flakes are 0.2–0.5 mm long and well oriented parallel to the foliation. Most of the biotite is reddish brown, but in some thin sections it is greenish brown. Alteration to chlorite was noted in several thin sections. Incipient alteration is indicated by pale brown or green color, low or bright interference colors, and inclusions of brown rutile, leucoxene, hematite, and magnetite along the cleavage planes.

Chlorite shows more irregularity in its distribution and mode of occurrence than the other micaceous minerals. There are two generations of chlorite: the early small flakes that occur with muscovite and biotite, and the late large flakes that are at angles to the plane of foliation. The early flakes are pleochroic in green and pale green and show brownish-gray to bluish interference colors. Much of this chlorite is next to the minute veinlets of quartz that are common in most of the phyllite. The late chlorite is very pale green to colorless and has dark-bluish-gray interference colors. It commonly contains helicitic inclusions of quartz, graphite, and magnetite.

Albite when present is in small grains that are usually untwinned.

Cordierite porphyroblasts are common in many layers of dark-gray biotite phyllite exposed in the canyon of Bear Creek and along Big Creek in the southern part of the Bucks Lake quadrangle. On the foliation surface these porphyroblasts form tiny knots 1 mm long that are enveloped by biotite (fig. 7). Thin sections show two generations of cordierite. The earlier one, cordierite I, contains rows of helicitic inclusions of quartz, biotite, and magnetite. The rows are at an angle to the foliation that envelops the cordierite (fig. 8). The later one, cordierite II, either grew around cordierite I and included the foliation that enveloped cordierite I or formed new grains in which rows of inclusions form S-shaped curvature joining the external foliation at the crystal borders. Alteration to muscovite and chlorite and also to pinite is common.

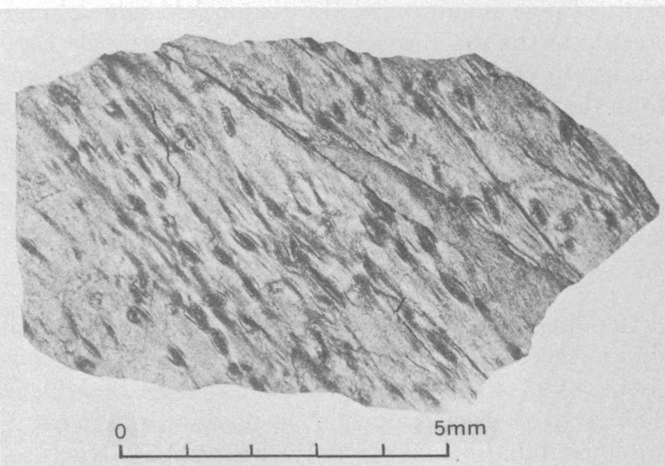


FIGURE 7.—Small cordierite porphyroblasts in a dark biotite phyllite that shows irregular wrinkling with axes that parallel the major northwest fold axis. Calaveras Formation, location 104 on Bear Creek.

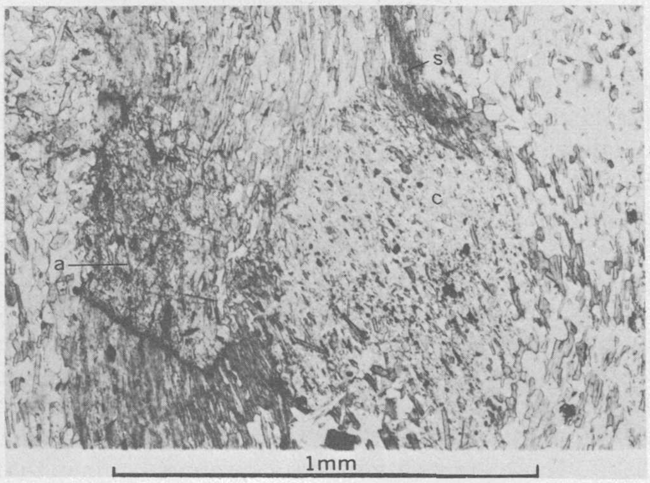


FIGURE 8.—Photomicrograph of cordierite (c), andalusite (a), and sillimanite (s) in biotite schist on Bear Creek (loc. 85). In the early cordierite, the internal *s* plane, shown by rows of inclusions, is at an angle to the external foliation. Ordinary light.

Numerous large porphyroblasts of cordierite occur in the phyllite in the northwest corner of the Pulga quadrangle northeast of Jones Meadow (fig. 5). These porphyroblasts and those at Chambers Peak are late. They contain helicitic inclusions of quartz, biotite, and magnetite that are well alined parallel to the foliation of the host phyllite, even in the centers of the crystals. The quartz inclusions are usually small and round. In some quartz-rich layers, however, quartz inclusions are large enough to make cordierite poikiloblasic, or it may even seem interstitial. The biotite flakes in cordierite are smaller than those in the host phyllite. Cracks and border zones of cordierite are altered to pinite, more rarely to sericite. Tiny grains of magnetite are in rows parallel to the foliation. They are more numerous in the central parts than in the border zones of the cordierite metacrysts.

Metacrysts of cordierite near the contact of the Grizzly pluton south of Rag Dump (loc. 954) contain rows of helicitic inclusions of biotite and magnetite. These rows are at an angle to the plane of foliation and prove that this cordierite crystallized early.

Anthophyllite in long prisms occurs with cordierite northeast of Jones Meadow (fig. 6). The prisms (1–3 mm long) either are included in cordierite or are among biotite and quartz in the cordierite-bearing layers.

Cummingtonite in needles and slender prisms with $Z \wedge c = 15°–16°$ occurs instead of anthophyllite in many cordierite-bearing layers.

Andalusite in the cordierite-andalusite-sillimanite schist (fig. 8) includes rows of inclusions of ilmenite and quartz that are parallel to the plane of foliation. This andalusite crystallized late, most likely contemporaneously with cordierite II.

Sillimanite was found in a few thin sections of the cordierite-bearing phyllite along Bear Creek. It forms small wisps around and near the cordierite and andalusite (fig. 8). The sillimanite-bearing rock contains very little muscovite and no chlorite or potassium feldspar.

Garnet occurs only in a few localities. Red anhedral to subhedral grains, 5–12 mm long, crystallized in biotite phyllite east of the Oliver Lake pluton (loc. 1161). These grains are in coarse-grained laminae that consist mainly of quartz with some large flakes of biotite. Numerous tiny garnets occur in the fine-grained dark-gray muscovite-biotite phyllite exposed on the north slope of Hartman Bar Ridge in the south-central part of the Bucks Lake quadrangle (loc. 421). Small garnets are included in some of the cordierite at Chambers Peak in the Pulga quadrangle.

Magnetite is ubiquitous. It occurs in grains of various sizes (0.01–0.5 mm) or is disseminated. Alteration to hematite is common.

Pyrite in small cubes and in anhedral grains occurs locally. Also this mineral alters to hematite.

Tourmaline in tiny euhedral prisms is common in all phyllite, but not abundant.

Sphene and rutile are included in chlorite that was derived from biotite. Sphene is in euhedral to anhedral small grains; alteration to leucoxene is common.

Two samples of phyllite from the canyon of Bear Creek (Nos. 85, 104) were analyzed chemically (table 1). Sample 85 contains cordierite and some andalusite and sillimanite. Biotite in 0.03–0.05-mm long flakes is the major dark constituent. Sample 104 is a dark layer in phyllite; it contains abundant biotite, graphite, and magnetite. Some late chlorite transects the earlier minerals. The analyses show that both layers are poor in calcium and contain iron and magnesium in about equal amounts.

MARBLE

Two layers of gray to white marble are exposed along the Middle Fork of the Feather River about 0.2 miles west of the mouth of Bear Creek. Each layer is about 20 m thick (shown as one layer on pl. 2) and consists of thin-bedded gray to white marble that grades to carbonate-bearing black phyllite above and below. These layers are discontinuous and grade parallel to the strike into an epidote-rich phyllite.

A very similar gray to white layered marble is exposed just north of the Pulga quadrangle 1 mile west-northwest of Campbell Lake (loc. 1234). This marble is coarse grained because of contact metamorphism by the Grizzly pluton. It is underlain by a metabasalt and metachert and overlain by black phyllite that contains numerous lenses of epidote, many as much as 15 cm long. The phyllite exposed on Big Creek in the central part of the Bucks Lake quadrangle includes several carbonate-bearing layers. These marble layers were not analyzed chemically. They probably consist mainly of calcium carbonate, as do the two analyzed layers in this area.

STRUCTURE

MAJOR FEATURES

The striking structural feature in the area, the curvature of the trends of metamorphic wallrocks around granitic plutons, is best shown by the structures in the two branches of the Calaveras Formation that wrap around the plutons. The second folding on steeply plunging axes is especially well demonstrated by intricately folded metachert that is in the triangular areas between the plutons. The change in the trend of the major axes from the northwesterly direction first to westerly then to southerly follows closely the direction of the northern and western walls of the nearby plutons and is clearly a result of the shouldering effect of the invading magma. This is especially well demonstrated in the western part of the Pulga quadrangle, where folds are squeezed perpendicular to the contact of the Grizzly pluton and the trends of the major fold axes parallel the curving contact. In the northwestern part of the Pulga quadrangle, the major fold axes plunge steeply to the southwest, and in the western part they plunge to the south. Thus the beds become younger from the north to the south, provided that right side is up as determined from the relation between bedding and cleavage. This relation indicates that the metasedimentary rocks exposed near Rag Dump represent the upper part of the Calaveras Formation.

BEDDING

Bedding is well preserved in the metachert in which thin micaceous layers are interbedded with layers consisting of 95–100 percent quartz (figs. 4, 9). Bedding is difficult to observe in much of the phyllite, and in many outcrops foliation is the only measurable structure. Where quartz-rich or carbonate-bearing layers are interbedded, as along Big Creek, the bedding is discernible because of differences in color, grain size, or amount of micaceous minerals and quartz. Bedding is well preserved in some of the phyllite exposed in the northernmost part of the area, where layers of metachert are interbedded. Phyllite there contains thin layers of metachert not shown on plates 1 and 2 and also layers, 1–5 m thick, in which thin quartz-rich beds alternate with micaceous beds. The thickness of individual beds in these layers is 0.5 cm, whereas thicker beds are common in the normal phyllite.

FOLDS

Three major folds on a regional scale are evident in the Calaveras Formation (pls. 1, 2): (1) An anticline on an axis that plunges steeply to the east is well exposed in the canyon of the North Fork of the Feather River in the northeastern part of the Pulga quadrangle. The south flank of this fold wraps around the southern part of the Oliver Lake pluton, and the north flank encircles it in the north. (2) A large gentle anticline whose axis plunges east-southeast is indicated by curving of the bedding in phyllite and by distribution of interbedded metachert on Big Creek in the central part of the Bucks Lake quadrangle. This anticline is interrupted in the west and in the south by intrusive quartz diorite and covered in the east by Tertiary pyroclastic andesite. (3) A synclinal structure of similar phyllite and metachert south of these plutonic and volcanic rocks is revealed by attitudes of beds on the steep slopes of the canyon of Bear Creek. Small folds whose axes plunge west and northwest are exposed southeast of Red Ridge and north of the Middle Fork on the northeast flank of this syncline.

Evidence of two sets of folds in the Calaveras Formation outside the contact aureoles of the plutons is provided by good exposures along the Middle Fork of the Feather River. East of Sherman Bar small folds on northwest-plunging axes are common. Axes of these folds parallel the lineation shown on plate 2. Near Cleghorn Bar, where beds dip to the east, small folds have axes that plunge steeply northeastward. In some outcrops between these two locations, two sets of folds are evident. The axis of the major set trends northwest; the axis of the second set trends east or northeast and plunges either southwest or northeast. The large anticline in the central part of the Bucks Lake quadrangle is on this second axis. The axis of small folds on its northeast flank trends northwest, and lineation on its south flank plunges southwest. This indicates that the first (major) folds on the northwest axis were refolded on the easterly (second) axis.

Small folds on the northwesterly axis are common in metachert on the East Fork of Big Creek in the central part of the Bucks Lake quadrangle and on the logging road following the north slope of the Bear Creek canyon. In the latter locality, small isoclinal folds on this major axis are common also in phyllite and are then accompanied by a well-developed steep axial plane cleavage.

Folds around the steeply plunging second axis and the lineation are well exposed in the northern part of the Pulga quadrangle near Long Lake (fig. 9) and

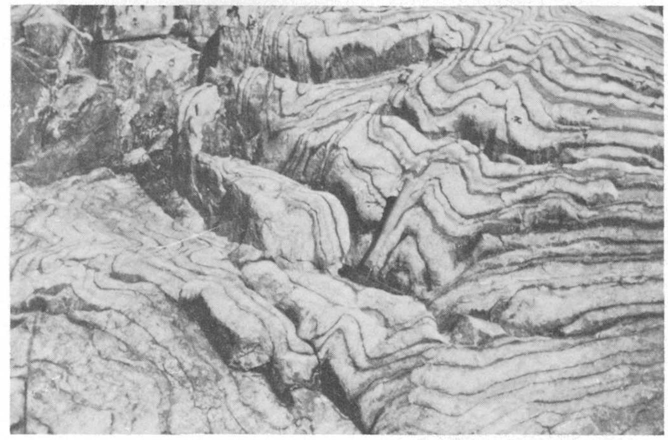


FIGURE 9.—Small folds with steep axes in metachert of the Calaveras Formation east of Long Lake. Hammer handle is parallel to fold axes. View is eastward. Axial plunge is 70° NW.

Campbell Lake and on Chambers Peak. Several plunges were measured (pl. 1), and it seems that the folding in these places was intensified and the plunge of the axis may have changed during the emplacement of the plutons. The plunge of the second fold axes elsewhere is less steep, and the trends are more regular.

Near Jones Meadows, at the northwest corner of the Pulga quadrangle, the interbedded phyllite-metachert sequence is tightly folded on an axis that plunges steeply to the south-southwest. The direction of the second fold axes that can be measured in the outcrops varies, and in some outcrops, as on Big Kimshew Creek, two sets of minor fold axes can be measured, one trending subparallel to the contact of the pluton and the other plunging away from it. There the younger beds are to the south, where layers of hornblende gneiss and metabasalt are interbedded with quartzite.

FOLIATION

In much of the phyllite, foliation is the only measurable *s* plane. It parallels the axial planes of small folds. On the flanks of large folds, it is either parallel to the bedding or makes a small angle with it.

In the folded metachert and in the interbedded phyllite, foliation is commonly parallel to the axial plane. In a few outcrops near the plutonic rocks, a fan-shaped arrangement of cleavage indicates tightening of the folds after the development of the axial plane cleavage. This is particularly clear in the outcrops 1 mile south of

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Spanish Peak and in the intensely folded metachert that fills the triangular areas between the plutons in the northern part of the Pulga quadrangle (fig. 10) where this feature as well as the irregularity in the orientation of the fold axes can be logically attributed to a later squeezing by the invading plutons.

FIGURE 10.—Fan-shaped arrangement of cleavage (s_2) at the hinges of folds on glaciated horizontal surface of metachert of the Calaveras Formation east of Long Lake. Minor faults and breakage are common at the hinges of tight folds.

LINEATION

The strongest linear element that can be observed in the outcrops is parallel to the axes of the folds—either first or second generation. The lineation is usually an intersection of beddding and foliation and is a direction of strong stretching, as shown, for example, by strongly elongated lenses of quartz in the phyllite. It is well developed in all rocks and can be readily measured. The second linear element appears as an axis of minor folds in the metachert and locally also in the phyllite. Many outcrops of phyllite in the southern part of the Bucks Lake quadrangle show a fine wrinkling of the plane of foliation in outcrops where this plane is parallel to the bedding.

METAVOLCANIC SEQUENCE

Metavolcanic rocks southwest of the Melones fault are divisible into three lithologic units that were named the Franklin Canyon, Duffey Dome, and Horseshoe Bend Formations as described under the heading "Rocks of the Area."

FRANKLIN CANYON FORMATION

DISTRIBUTION

A thick heterogeneous sequence of meta-andesite, metadacite, metasodarhyolite, and associated metatuffs traversing the south-central part of the Bucks Lake quadrangle (pls. 2, 3) is here named the Franklin Canyon Formation. The type section in Franklin Canyon on the Middle Fork of the Feather River (secs. 3, 4, 5, T. 22 N., R. 8 E.) consists of meta-andesite, metadacite, and metatuff about in equal amounts and includes only thin discontinuous layers of metasodarhyolite, whereas the "a" section, a reference section along Willow Creek west of Mount Ararat, contains abundant metasodarhyolite and less metatuff. A questionable Paleozoic age is assigned to the Franklin Canyon Formation because of its continuity with the Paleozoic section of Ferguson and Gannett (1932) to the south (Hietanen, unpub. data).

On the Middle Fork of the Feather River, the trace of the contact between meta-andesite of the Franklin Canyon Formation and the phyllite of the Calaveras Formation is at an angle to the strike of bedding in the Calaveras. A rather straight, steeply dipping contact and an angular unconformity near Dogwood Peak (pl. 2) and to the northwest indicate a fault. This fault, the Dogwood Peak fault on plate 2, extends from the east slope of Dogwood Peak to Faggs Ranch, where it terminates in an ultramafic body. A thinner unit consisting of meta-andesite, metadacite, and metatuff is exposed on the southwest side of the Rich Bar fault. A section through this unit is well exposed along Big Creek. The structural relations between these rocks and the underlying Calaveras Formation north of Silver Lake and along the Middle Fork at the east border of the Bucks Lake quadrangle indicate an angular unconformity. North of Silver Lake the meta-andesite rests on successively older beds of the metachert and phyllite of the Calaveras Formation toward the northwest.

The southwest boundary of the Franklin Canyon Formation is marked by thin bodies of serpentine and talc schist that extend westward from the vicinity of the Little California mine and probably conceal another fault. This fault, the Camel Peak fault on plates 2 and 3, continues southward to the American House quadrangle, where it passes the east side of Camel Peak and is marked by juxtaposition of structures and by elongate bodies of serpentine. The west end of this fault south of the Granite Basin pluton is concealed by metagabbro and metadiorite.

The lowest unit in the Franklin Canyon Formation near Dogwood Peak consists of several massive flows of meta-andesite separated by thin layers of dark phyllitic metatuff. Toward the west and northwest, metadacite is intercalated with meta-andesite, and farther to the northwest it becomes the major rock type with less meta-andesite and more metamorphosed sodarhyolite. Most of this metamorphosed sodarhyolite is in the central part of the southern metavolcanic belt, northwest of Mount Ararat. Layers of metatuff, pyroclastic rocks, and tuffaceous metasediments are interbedded with all metavolcanic rocks. Only the largest continuous occurrences of metatuff are shown on the map (pl. 2). Others ranging from a few centimeters to several meters in thickness are common.

Metadacite and associated metamorphosed soda-rhyolite, similar to those in the Bucks Lake quadrangle, are exposed in the western part of the Pulga quadrangle. Structural relations west and southwest of Jones Meadow suggest that these metavolcanic rocks overlie the metasedimentary rocks of the Calaveras Formation. The contact is conformable in some places, unconformable in others. Faults separate two small occurrences of metadacite and metarhyolite from the metasedimentary rocks of the Calaveras Formation in the vicinity of Five Corners at the west border of the Pulga quadrangle. On the west side these occurrences are bordered by a large body of metamorphosed hornblende quartz diorite.

A few thin discontinuous layers of metachert, quartzite, phyllite, and marble are interbedded with the metavolcanic rocks. Most of the quartzite and metachert is at the west end of the southern belt.

PRIMARY VOLCANIC STRUCTURES

Pyroclastic structures, such as volcanic breccia, bombs, lapilli, and rare pillows, are easily recognizable —even when deformed—in all the metavolcanic rocks. Bombs and lapilli are especially common in metadacite and meta-andesite. Good exposures on the Middle Fork of the Feather River offer the best material for a study of these structures. Most of the meta-andesite and metadacite east of the mouth of Dejonah Creek consists of agglomerate in which volcanic bombs, 5–80 cm long, are embedded in a fine-grained matrix. Interbedded tuffaceous layers contain pebbles of lapilli size (¼–5 cm long). Similar structures are striking in many tuffaceous layers on the Middle Fork of the Feather River east of Cleghorn Bar (fig. 11). These layers are intercalated with others that contain large plagioclase crystals. Farther to the east, at the east border of the Bucks Lake quadrangle, pillow structures are well preserved in meta-andesite.

Most of the meta-andesite exposed in roadcuts on Big Creek in the central part of the Bucks Lake quadrangle is agglomerate and contains interbedded layers of lapilli tuff. The meta-andesite on the east slope of Dogwood Peak and that northeast of Silver Lake contain, in addition to pyroclastic material, several thick flows of porphyritic lava. The individual flows, 20–100 m thick, are separated by thin (about 1m thick) layers of fine-grained metatuff.

PETROGRAPHIC DESCRIPTION

META-ANDESITE

Most of the meta-andesite is fine grained and greenish gray with scattered small phenocrysts of plagioclase.

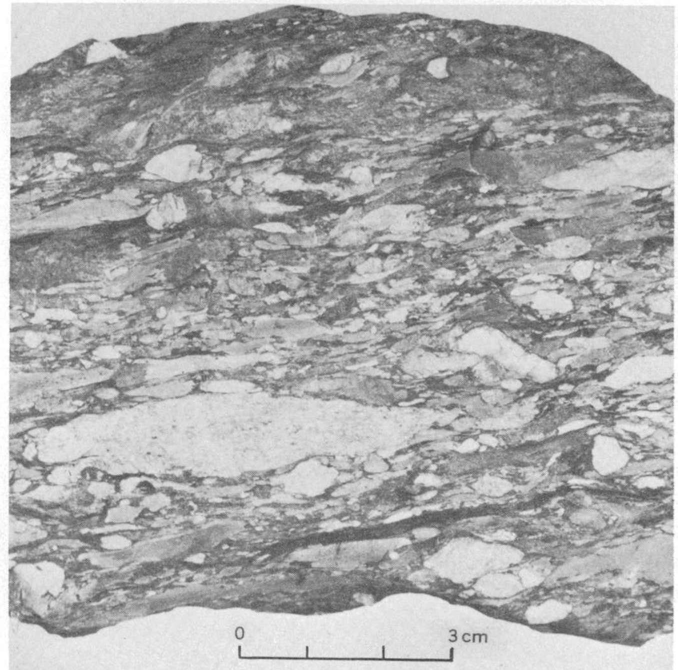


FIGURE 11.—Metatuff containing stretched lapilli. Franklin Canyon Formation, Cleghorn Bar on the Middle Fork of the Feather River (loc. 331).

Coarse-grained porphyritic varieties occur in thick flows on Dogwood Peak, on Schneider Creek, and north of Silver Lake. At these localities large phenocrysts (½–2 cm long) of plagioclase and pyroxene are oriented at random, giving the rock the appearance of undeformed and unaltered recent lava. The thin sections show, however, that these rocks are completely recrystallized and consist of albite, epidote, actinolite, and chlorite with only occasional remnants of primary minerals such as augite. Accessory minerals (pyrrhotite, pyrite, magnetite, and ilmenite) are partly altered to hematite; sphene is partly altered to leucoxene. In most meta-andesite numerous tiny grains of sphene—most altered to leucoxene—are included in epidote, chlorite, and actinolite.

The amounts of major constituents in common meta-andesite vary. The ranges in percent are albite 10–30 (rarely 40), epidote 25–60, actinolite 15–30, chlorite 0–20, quartz 0–10. Sphene or leucoxene constitutes as much as 3 percent of the rock. Some layers contain as much as 98 percent actinolite, and other layers are exceptionally rich in epidote. Albite includes numerous small grains of epidote and some sericite. In several thin sections aggregates of chlorite and actinolite have outlines of augite, but remnants of augite are rare elsewhere, except on Dogwood Peak.

Actinolite is in small (0.01–1 mm long) prisms that are oriented at random or subparallel to the foliation. Small grains of epidote either are in large groups or fill the interstices between the actinolite prisms. Radial or fan-shaped arrangement of long thin aggregates of albite and epidote or of epidote and actinolite, such as is seen in localities 193 and 335, is clearly a relict texture inherited from the orientation of slender plagioclase crystals in spherulitic lava.

In the porphyritic varieties of meta-andesite, large phenocrysts of albite include abundant epidote and muscovite. The included epidote is in subhedral to anhedral grains of medium size, whereas muscovite is in rows of tiny laths. The rows are parallel to the cleavage of albite, and flakes are oriented perpendicular to it or have a radial arrangement. The groundmass consists of small laths of albite, grains of epidote, and prisms of actinolite. The albite laths have numerous tiny inclusions of epidote. On Dogwood Peak, phenocrysts of augite are only partly altered to chlorite, and phenocrysts of plagioclase, containing much less albite than elsewhere, consist mainly of epidote and muscovite.

Amygdules are scarce; they consist of epidote and chlorite. Numerous round light-green aggregates, 1–2 cm long, consisting of a mixture of fine-grained albite and epidote with some actinolite and chlorite, occur in a few localities, as northeast of Silver Lake (loc. 396). East of Cleghorn Bar (loc. 334) similar round light-green aggregates are embedded in dark-green actinolite-rich matrix between the pillows (fig. 12). The outermost layer of the pillows consists of epidote and albite in radial arrangement that is reminiscent of the original spherulitic texture.

Chemical analysis of meta-andesite (No. 463, table 1) shows a high percentage of calcium, iron, and aluminum and a low content of silicon and alkalies. Epidote in this specimen has $\alpha=1.719\pm0.001$, $\beta=1.731\pm0.002$, $\gamma=1.740\pm0.002$ indicating 12 mol percent of iron end member (Winchell and Winchell, 1951, p. 449). Some of the amphibole is colorless tremolite with $\alpha=1.624\pm0.001$; most is light-green hornblende with $\gamma=1.663\pm0.001$ and a specific gravity of 3.14.

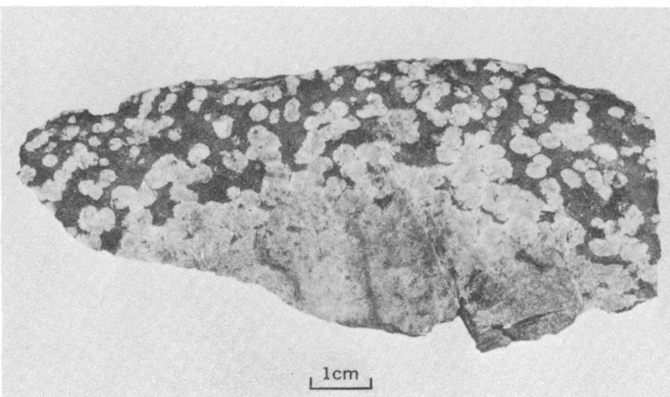


FIGURE 12.—Part of the outer rim of a pillow in meta-andesite of the Franklin Canyon Formation east of Cleghorn Bar (loc. 334). Light-colored round spherulites consist of epidote, albite, actinolite, and sphene. The dark matrix is epidote, chlorite, actinolite, and sphene.

METADACITE

Metadacite is similar to meta-andesite in appearance except for a somewhat lighter color. The main mineralogic difference is that the metadacite contains quartz phenocrysts and amygdules (fig. 13). Averages of estimated percentages of the major constituents are albite (An_{5-10}) 30, quartz 25, epidote 20, actinolite 15, chlorite 7, muscovite 1, biotite 1, accessory minerals 1. Common accessory minerals are magnetite, ilmenite, pyrrhotite, pyrite, and sphene that is partly altered to leucoxene. Abundant pyrite occurs in places, as for instance at Willow Creek near the Hose mine. Tourmaline is rare.

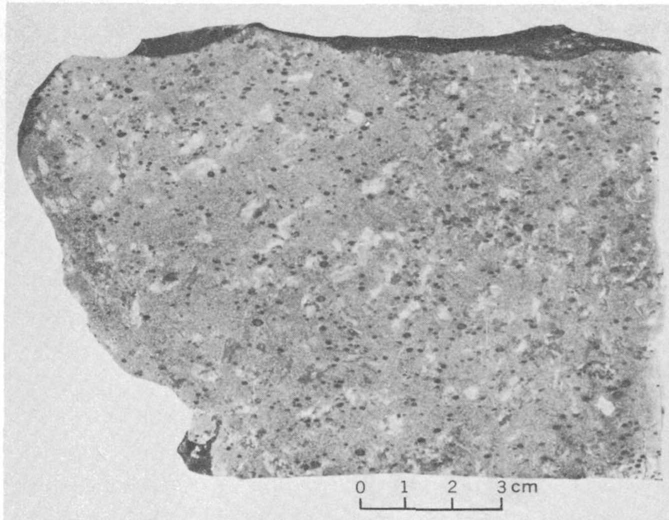


FIGURE 13.—Phenocrysts of albite (white) and amygdules of quartz (round dark spots) in metadacite of the Franklin Canyon Formation on Taylor Creek south of Meadow Valley (loc. 443).

Phenocrysts of albite include epidote and tiny flakes of muscovite. Many are granulated as are also the quartz phenocrysts. The groundmass is a fine-grained granoblastic mixture of albite, quartz, epidote, actinolite, and chlorite. Secondary veinlets of quartz are common, and some of the rocks mapped as metadacite could be classed as meta-andesite containing veinlets of quartz. Most of the veinlets are folded. They probably were originally cracks that were filled by quartz before or at the beginning of deformation, as were also the vesicles.

Comparison of the chemical analysis of metadacite (No. 464, table 1) with that of meta-andesite (No. 463, table 1) shows that the metadacite contains much less calcium, aluminum, and iron and more silicon and sodium.

TABLE 1.—*Chemical composition and molecular norms of metamorphosed igneous and sedimentary rocks from the Bucks Lake quadrangle*

[Analysts: E. F. Munson for sample 134; C. L. Parker for samples 796, 532; V. C. Smith for samples 465, 551, 85, 484; G. O. Riddle for samples 463, 464, 461, 104]

Specimen	134	796	532	465	551	463	464	461	85	104	484
Rock type	Peridotite partly serpentinized	Metagabbro	Metadiorite	Metadiorite	Metabasalt	Meta-andesite	Metadacite	Metarhyolite	Andalusite sillimanite cordierite schist	Biotite phyllite	Marble
Locality	Meadow Valley Creek	⅓ mile south of Robinson mine	South of Coldwater Creek	China Gulch	1 mile west of Grizzly Mountain	China Gulch		Hose mine	Bear Creek northeast of Lookout Rock	Bear Creek east of Lookout Rock	Marble cone Middle Fork of Feather River
Chemical composition, in weight percent											
SiO_2	42.32	48.30	52.18	53.36	50.99	41.32	54.32	66.39	73.48	78.27	0.08
TiO_2	.06	.11	.43	.54	2.03	.75	.49	.40	.64	.53	0
Al_2O_3	2.44	20.52	16.93	15.20	13.47	19.90	16.99	15.28	11.94	10.26	.03
Fe_2O_3	2.60	1.81	3.80	2.56	1.48	5.07	2.50	1.97	.94	.32	.01
Cr_2O_3	.39	.....	.....	.....	.....	.....	.....	.....	.....	.....	0
FeO	5.42	3.62	4.93	4.95	10.96	6.10	4.34	2.61	3.76	2.86	.01
MnO	.13	.11	.16	.17	.22	.17	.11	.11	.09	.05	0
NiO	.27	.....	.....	.....	.....	.....	.....	.....	.....	.....	0
MgO	39.03	8.47	5.80	7.58	5.95	6.96	6.58	2.05	2.11	1.83	.56
CaO	2.28	13.42	10.25	10.36	8.04	14.85	8.94	5.03	.28	.42	55.34
Na_2O	.24	1.95	2.30	1.80	4.07	.94	1.93	4.08	1.23	1.00	0
K_2O	.03	.12	.05	.03	.21	.03	.05	.14	2.51	2.29	.01
P_2O_5	.01	.07	.13	.16	.18	.17	.10	.10	.05	.08	.01
CO_2	.18	0	.01	.03	.02	.02	.01	.02	0	.03	43.94
Cl	.01	0	.01	0.01	0	0	0	0	0	0	0
F	.01	.01	.03	.03	.03	.04	.02	.03	.08	.06	.01
H_2O^+	4.57	1.51	2.85	2.89	1.75	3.74	3.18	1.73	1.73	1.57	0
H_2O^-	.27	.04	.10	.08	.16	.02	.01	.01	.34	.02	0
Subtotal	100.26	100.06	99.96	99.75	99.56	100.08	99.57	99.95	99.18	99.59	100.00
Less O	.00	.00	.01	.01	.01	.02	.01	.01	.03	.03	
Total	100.06	100.06	99.95	99.74	99.55	100.06	99.56	99.94	99.15	99.56	
Chemical composition, in ionic percent											
SiO_2	37.21	44.70	50.25	51.31	48.71	40.23	52.43	63.17	72.73	77.05	0.06
TiO_2	.04	.08	.31	.39	1.46	.55	.36	.29	.48	.39	0
$AlO_{3/2}$	2.53	22.38	19.21	17.23	15.17	22.83	19.33	17.13	13.93	11.90	.03
$Cr^{+3}O_{3/2}$	.27	.....	.....	.....	.....	.....	.....	.....	.....	.....	0
$Fe^{+3}O_{3/2}$	1.72	1.26	2.75	1.85	1.06	3.71	1.82	1.41	.70	.24	.01
$Fe^{+2}O$	3.98	2.80	3.97	3.98	8.76	4.97	3.50	2.08	3.11	2.35	.005
MnO	.10	.09	.13	.14	.18	.14	.09	.09	.08	.04	0
NiO	.19	.....	.....	.....	.....	.....	.....	.....	.....	.....	0
MgO	51.14	11.68	8.32	10.86	8.47	10.10	9.47	2.91	3.11	2.69	.69
CaO	2.15	13.31	10.58	10.67	8.23	15.49	9.25	5.13	.30	.44	49.30
$NaO_{1/2}$	.41	3.50	4.29	3.36	7.54	1.77	3.61	7.53	2.36	1.91	0
$KO_{1/2}$	.03	.14	.06	.04	.26	.04	.06	.17	3.17	2.88	.01
$PO_{5/2}$	.01	.05	.11	.13	.15	.14	.08	.08	.04	.07	.01
CO_2	.22	.....	.01	.04	.03	.03	.01	.03	.....	.04	49.88
Cl	(.02)	.....	(.02)	(.02)	.....	.....	.....	.....	.....	.....	0
F	(.03)	(.03)	(.09)	(.09)	(.09)	(.12)	(.06)	(.09)	(.25)	(.19)	(.02)
OH	(26.81)	(9.32)	(18.31)	(18.54)	(11.15)	(24.29)	(20.47)	(10.98)	(11.42)	(10.31)	0
Total	100.00	99.99	99.99	100.00	100.02	100.00	100.01	100.02	100.01	100.00	100.00
Total anions	152.99	159.55	168.80	169.16	160.30	165.65	171.95	174.60	183.78	186.60	149.97
Catanorm, in molecular percent											
Q	.....	.....	8.70	10.20	.....	.....	12.71	26.34	50.45	57.71	.....
Or	0.15	0.71	.31	.18	1.28	.19	.31	.85	15.85	14.38	0
Lc	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.04
Ab	1.95	17.50	21.39	16.70	37.69	8.87	18.06	37.63	11.80	9.54	.....
An	5.27	46.86	37.19	34.62	18.43	52.55	39.13	23.59	.54	1.05	.....
Co	.....	.....	.....	.....	.....	.....	.....	.....	8.18	6.70	.02
Wo	1.70	7.68	5.84	6.94	8.51	9.36	2.50	.43	.....	.....	.....
En	21.80	14.38	16.65	21.73	13.18	8.49	18.93	5.81	6.23	5.37	.....
Fs	1.40	2.68	4.82	5.60	10.80	2.27	4.66	2.35	4.72	3.77	.....
Fo	60.36	6.74	.....	.....	2.83	8.78	.....	.....	.....	.....	.13
Fa	3.81	1.26	.....	.....	2.32	2.35	.....	.....	.....	.....	.....
Mt	2.58	1.89	4.13	2.78	1.60	5.57	2.72	2.12	1.05	.36	.01
Il	.08	.15	.62	.78	2.92	1.10	.71	.57	.95	.78	.....
Cm	.40	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Ap	.03	.15	.28	.35	.39	.37	.22	.21	.11	.18	.02
Cc	.44	.....	.03	.08	.05	.05	.03	.05	.....	.08	98.58
Hl	.04	.....	.03	.03	.....	.....	.....	.....	.....	.....	.....
Fr	.04	.02	.08	.07	.06	.11	.05	.10	.35	.25	.03
MgS	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	1.18
Total	100.05	100.01	100.07	100.06	100.04	100.08	100.03	100.06	100.24	100.16	100.01

TABLE 1.—*Chemical composition and molecular norms of metamorphosed igneous and sedimentary rocks from the Bucks Lake quadrangle*—Continued

Specimen	134	796	532	465	551	463	464	461	85	104	484
Rock type	Peridotite partly serpentinized	Metagabbro	Metadiorite	Metadiorite	Metabasalt	Meta-andesite	Metadacite	Metarhyolite	Andalusite sillimanite cordierite schist	Biotite phyllite	Marble
Locality	Meadow Valley Creek	⅓ mile south of Robinson mine	South of Coldwater Creek	China Gulch	1 mile west of Grizzly Mountain	China Gulch		Hose mine	Bear Creek northeast of Lookout Rock	Bear Creek east of Lookout Rock	Marble cone Middle Fork of Feather River
Mesonorm, in molecular percent											
Quartz			7.27	8.38			12.09	26.56	53.14	60.21	
Andalusite								.21	8.67	6.83	
Albite		12.25	21.39	16.70	32.94	1.11	18.06	37.63	11.80	9.54	
Anorthite		46.86	37.19	34.62	18.43	52.55	39.13	23.25			
Muscovite									9.16	8.98	
Biotite		1.13	.49	.29	2.05	.30	.49	1.36	14.89	12.75	0.10
Hypersthene		8.22	8.68	12.50	18.24	5.82	19.45	7.72			
Enstatite											.10
Actinolite		12.47	19.57	23.09	6.71	7.69	6.72				
Edenite		16.80			15.21	24.85					
Sphene		.23	.93	1.17	4.38	1.65	1.07	.86	.33	.63	
Magnetite		1.89	4.13	2.78	1.60	5.57	2.72	2.12	1.05	.36	.01
Ilmenite									.73	.37	
Apatite		.15	.28	.35	.39	.37	.22	.21	.11	.18	.02
Fluorite		.02	.08	.07	.06	.11	.05	.10	.35	.25	.03
Calcite			.03	.08	.05	.05	.03	.05		.08	98.58
Halite			.03	.03							
Magnesite											1.18
Total		100.1	100.7	100.6	100.4	100.8	100.03	100.06	100.24	100.16	100.02

METAMORPHOSED SODARHYOLITE

Metamorphosed sodarhyolite is very light gray to white and fine grained. Euhedral to subhedral phenocrysts of quartz and feldspar are common in some places; others show fragmental stuctures. Staining of the specimens shows very little if any potassium feldspar.

Thin sections confirm the almost complete absence of potassium feldspar. Estimated percentages of the major constituents are quartz plus albite 65–75, muscovite 5–15, chlorite 0–20, biotite 0–15, epidote 2–10, calcite 0–5. Magnetite, partly altered to hematite, and sphene are common accessory minerals. Some layers contain numerous cubic crystals of pyrite. Quartz phenocrysts are euhedral to subhedral and ½–1 mm long; many are granulated. Albite phenocrysts are twinned and include small grains of epidote and sericite. The groundmass is either granoblastic or lepidoblastic with albite in small laths. Sericite and chlorite or biotite are in laminae and in scattered tiny flakes. In some thin sections pseudomorphs after a ferromagnesian mineral, probably biotite or hornblende, consist of chlorite that includes small grains of epidote and magnetite. All chlorite is pale green and has a very low birefringence.

Abundant calcite occurs in light-gray metamorphosed sodarhyolite at Carpenter Bar on the Middle Fork of the Feather River (loc. 372) and on Little Bear Creek (loc. 623) 1½ miles northwest of Carpenter Bar. The main micaceous mineral in these rocks is chlorite, which occurs as individual flakes, clusters, and laminae. Some of the quartz and albite phenocrysts are fractured and granulated; calcite and small grains of quartz fill the fractures. Chemical analysis (No. 461, table 1) shows less calcium, iron, magnesium, and aluminum and more silicon and sodium than in metadacite.

METATUFF AND TUFFACEOUS METASEDIMENT

Tuffaceous layers interbedded with metavolcanic rocks are fine grained and foliated. The color ranges from dark greenish or bluish gray to light brownish gray. Their mineralogy is similar to the interlayered lavas. Andesitic metatuff consists mainly of epidote, actinolite, and some albite, magnetite, and sphene. Dacitic metatuff has, in addition to these minerals, quartz as small blebs and veins, and it contains more albite. Sodarhyolitic metatuff is rich in quartz and contains 15–25 percent each of albite and muscovite. Biotite or chlorite and epidote are commonly present, and magnetite and sphene occur as accessory minerals. Many layers of sodarhyolitic metatuff are laminated; the quartz-rich laminae are separated by laminae rich in muscovite or chlorite and epidote. Some layers of sodarhyolitic metatuff are exceptionally rich in quartz and grade to fine-grained gray to white granular sericite quartzite, which may represent weathering products of rhyolitic tuff layers.

Phyllitic layers intercalcated with meta-andesite and metadacite in the southern part of the Bucks Lake quadrangle contain more albite and epidote and less muscovite and chlorite (or biotite) than the regular metasedimentary phyllite. Large crystals of albite occur occasionally, and pebbly layers are common (fig. 11). These layers were originally tuffaceous sediments.

Some layers interbedded with metatuffs and tuffaceous metasediments contain carbonate as individual grains, clusters of grains, and small lens-shaped or layerlike bodies. Lenses of white marble, 5–20 cm long, are common in many layers exposed on the Middle Fork of the Feather River. Some of this carbonate is probably sedimentary. In the tuffaceous layers, however, albite and calcium carbonate crystallized from the anorthite component of the plagioclase at low temperatures, either during volcanism (spilite reaction) or later during regional metamorphism. Addition of CO_2 is necessary in either case. In a spilite reaction the CO_2 could have had a volcanic source; during metamorphism, CO_2 may have been added from a release elsewhere, as for instance, from a source where dolomite reacted with silica to form tremolite.

DUFFEY DOME FORMATION

DISTRIBUTION

Metabasalt is the major rock type of the Duffey Dome Formation, which forms an east-west-trending belt south of the Bucks Lake and Grizzly plutons. In the south this belt is bordered by serpentine exposed northwest of the Merrimac pluton. In the east it wraps around the Granite Basin pluton, grading over to metagabbro near the contacts of this pluton. A type section through the northern part of this formation is well exposed near Duffey Dome in sec. 16, T. 23 N., R. 6 E., in Pulga quadrangle. A reference section through the southern part of the formation is exposed along the road to Bear Ranch Hill in secs. 19 and 30, T. 23 N., R. 6 E. Steep outcrops on Bear Ranch Hill (see fig. 14) are a part of this metabasalt. In the canyon of the North Fork of the Feather River, a layer of metabasalt 400 m thick is exposed about half a mile north of Pulga, where it is exposed above a metatuff and metachert.

The Duffey Dome Formation is believed to be probably Paleozoic and possibly somewhat younger than the Franklin Canyon Formation on the basis of structural relations east of the Granite Basin pluton. Fold axes in this vicinity plunge northwest, indicating that the younger beds are to the west. The eastward plunge of fold axes along the contact with the Horseshoe Bend Formation west of the Granite Basin pluton suggests that Horseshoe Bend is younger. Elsewhere metaigneous rocks or faults separate these three formations.

Some discontinuous layers of metarhyolite rich in potassium feldspar, metatuff with layers rich in quartz, and thin-bedded quartzite and metachert are intercalated with the metabasalt. A few layers and dikelike bodies of light-gray hornblende-albite rock with considerable quartz also are interbedded (not shown on pl. 1). Small bodies of white marble are exposed in a roadcut just south of Grizzly Creek.

PETROGRAPHIC DESCRIPTION

METABASALT

The metabasalt is dark greenish gray to black and commonly foliated; hornblende prisms are subparallel to the foliation. Most of the metabasalt could be classified as amphibolite. Near Grizzly Summit parts of it grade into a massive lighter colored hornblende-plagioclase-quartz rock in which hornblende prisms are oriented at random.

Thin sections show that green hornblende (α=1.639 ±0.001, γ=1.666±0.001 in specimen 551) is a major constituent of all the metabasalt in amounts ranging from 45 to 65 percent. Albitic plagioclase (10–50 percent), epidote (2–20 percent), and magnetite (1–10 percent) are always present. The light-colored parts of metabasalt near Grizzly Summit contain as much as 15 percent quartz. Some of the quartz occurs in clusters and small lens-shaped aggregates. This quartz may have originated in recrystallized fragments of older quartzite or metachert that were incorporated into lava during the eruption. Some of the light-colored rock is a result of segregation of quartz and albitic plagioclase into small masses and dikelike bodies. The amphibole crystals in all light-colored masses are larger and lighter green than they are elsewhere in the same rock. Next to the quartz veins and lenses, they are similar to the actinolite in the metadacite.

Chemically the metabasalt (No. 551, table 1) differs from the meta-andesite in its higher content of silicon, ferrous iron, and sodium and lower content of aluminum, ferric iron, and calcium.

Medium-grained metabasalt that is much less deformed than the common type is exposed half a mile south of Duffey Dome. This metabasalt contains biotite, quartz, and abundant epidote in addition to the common major constituents, hornblende and plagioclase. Part of the hornblende is in large crystals that have ragged ends, are randomly oriented, and show pleochroism Z=blue green, Y= green, X=pale green. Biotite is in clusters of small greenish-brown grains. Most of the epidote is in large subhedral grains among hornblende, plagioclase (An_{15}), and quartz, but some of it forms small inclusions in hornblende. Ilmenite, partly altered to leucoxene, or surrounded by sphene, is a common accessory mineral. Some of the plagioclase is in large subhedral crystals that include small epidote and hornblende crystals.

METARHYOLITE

Small bodies of light-bluish-gray fine-grained metarhyolite are interlayered with metabasalt north of the Merrimac pluton. The texture in most outcrops is porphyritic, but in some is trachytic and equigranular. Fragmental textures are common. Phenocrysts of quartz and feldspar are embedded in a fine-grained slightly schistose groundmass. Staining of cut surfaces shows that these rocks are rich in potassium feldspar, in contrast with the soda-rich end members of the Franklin Canyon Formation.

The potassium feldspar either is untwinned or shows a weak microcline twinning under the microscope. Some of the individual phenocrysts consist partly of albite and partly of microcline. Large holoblasts of muscovite are common near many phenocrysts. Biotite is the most common dark constituent and occurs in tiny flakes subparallel to the foliation. Large flakes of grayish-green chlorite with ultrablue interference colors are either in clusters or rim some of the quartz veins. Chlorite includes a sphenelike mineral and is most likely a secondary mineral formed by introduction of a hydrous molecule after the major period of recrystallization. Epidote is in scattered small grains or in clusters. Some large grains of epidote occur next to quartz veinlets, which transect most of the metarhyolite at irregular intervals. Magnetite, ilmenite, apatite, and sphene are the common accessory minerals.

METATUFF

Greenish-gray fine-grained schistose layers consisting mainly of amphibole and chlorite, with some albite, epidote, quartz, magnetite, and rutile or sphene, are interbedded with metabasalt and probably represent metamorphosed tuff layers. The amphibole is commonly actinolite and rarely green hornblende. Most of these layers are only a few meters thick and are therefore not shown on plate 1.

Metatuff of rhyolitic composition is interbedded with metarhyolite near Palmetto and on the road to Bear Ranch Hill southeast of Kister. These metatuffs are very light bluish gray and rich in quartz. Many layers are laminated and all are strongly deformed. Phenocrysts of quartz and albite (An_5) are common. Muscovite is the major micaceous mineral. Potassium feldspar, biotite or chlorite, some epidote, and magnetite are the other constituents.

A few layers of metatuff recrystallized to amphibole schist are interbedded with metabasalt south of Duffey Dome. The major constituent in these layers is actinolite or actinolitic hornblende (40–70 percent). Chlorite and (or) biotite (5–20 percent) occur with it or form thin laminae that include epidote. The light-colored constituents are albite (An_{8-10}) and quartz. Magnetite, sphene, and brown rutile are the accessory minerals. The large amount of actinolitic hornblende indicates that these metatuffs are of basaltic composition.

A unit of thin-bedded hornblende-biotite-quartz-plagioclase gneiss is well exposed on roadcuts and on railroad cuts 0.7–1 mile north of Pulga. The beds are 1–4 cm thick and have alternating assemblages of hornblende-quartz, hornblende-biotite-quartz, hornblende-albite-quartz, and biotite-quartz. The range in amount of dark constituents in individual thin layers from 5 to 60 percent results in strong color contrasts. Layers of biotite quartzite are interbedded on the northern (lower?) part of this unit. On the south side it is bordered by a body of serpentine. The composition of the layers indicates that this unit contains alternating layers of tuffaceous material (hornblende-albite-quartz layers) and sedimentary material rich in quartz.

Interbedded hornblende and biotite-plagioclase gneiss with a discontinuous layer of biotite quartzite is exposed north of the thin-bedded hornblende-biotite gneiss. The quartzite is light gray and thin bedded and resembles the metachert of the Calaveras Formation exposed on the south side of Bucks Lake.

Metabasalt interbedded with the metasedimentary and tuffaceous layers is dark and fine grained. It consists of hornblende, albite, epidote, and chlorite and is mineralogically and texturally similar to the metabasalt of the Duffey Dome Formation.

QUARTZITE AND MARBLE INTERBEDDED WITH METAVOLCANIC ROCKS

The quartzite interbedded with the metavolcanic rocks is light gray to white and thin bedded. Micaceous laminae separate thin (1–3 cm thick) layers of quartz. Some layers, such as those just south of Grizzly Mountain and another half a mile north of Kister, have textures typical of metachert. The quartzite layers south of Grizzly Mountain are very fine grained and are irregularly traversed by tiny veinlets of more coarse-grained quartz. More thorough recrystallization elsewhere has produced equigranular granoblastic white quartzite in which only the bedding typical of less altered metachert indicates the origin. For example, in the quartzite half a mile north of Kister, individual layers 2–3 cm thick consisting of white medium-grained quartzite are separated by micaceous layers that are only 2–6 mm thick.

The marble exposed at Carpenter Bar on the Middle Fork of the Feather River consists of white to gray medium-grained calcium carbonate. It grades to micaceous and actinolite-bearing calcareous phyllite, presumably a metatuff, that contains lenses, 10–15 cm long, of similar white marble.

Abundant contact minerals such as epidote and grossularite have crystallized in the marble south of Grizzly Creek. The epidote is dark green to black, with shiny crystal faces. Euhedral crystals occur in the cavities from which calcium carbonate has weathered out. Grossularite is in large brown euhedral crystals that show anomalous gray interference colors and strong zoning under the microscope.

STRUCTURES DUE TO DEFORMATION

Metavolcanic rocks were folded and deformed with the metasedimentary rocks and thus show similar structural features. The compact flows are much less deformed than the softer tuffaceous layers. Central parts of some thick flows seem undeformed, whereas the tuffaceous layers are strongly schistose, with lapilli drawn out to spindles 10 times longer than their shortest dimension. (See Hietanen, 1951, p. 589–590.) All gradations between these two extremes occur.

Some of the pyroclastic andesite on Big Creek shows very little deformation, if any, and thus acted as a thick compact unit similar to that of the flows. These layers may have been welded during the eruption. Part of the meta-andesite on the east slope of Dogwood Peak shows slightly deformed fragmentary structures.

Foliation can be measured in 80 percent of the outcrops, and lineation in about 50 percent. Micaceous minerals are well oriented parallel to the foliation and lineation. Actinolite in the meta-andesite and metadacite is commonly subparallel to these structures and is rarely oriented at random. Parallel orientation of green hornblende in the metabasalt lends a foliated structure and fairly good lineation to most of these rocks. On Bear Ranch Hill metabasalt is strongly sheared and stretched; it breaks into pencil-shaped fragments parallel to an almost vertical lineation (fig. 14) that also parallels fold axes.

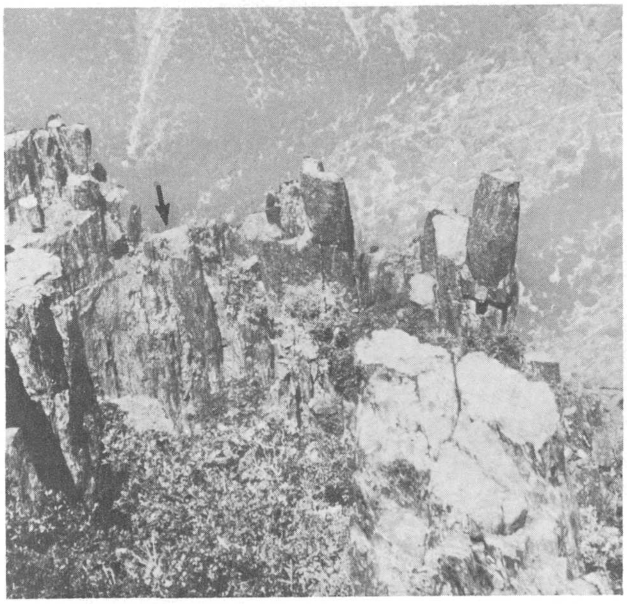


FIGURE 14.–Strong stretching parallel to a nearly vertical lineation (arrow) and fold axis in metabasalt of the Duffey Dome Formation at Bear Ranch Hill.

HORSESHOE BEND FORMATION

DISTRIBUTION AND MAJOR STRUCTURES

The sequence of interbedded metasedimentary and metavolcanic rocks exposed in the southwestern part of the Bucks Lake quadrangle and in the southern part of the Pulga quadrangle is lithologically different from the formations described earlier and, therefore, could not be included in any of them. This sequence is here named the Horseshoe Bend Formation after Horseshoe Bend of the Little North Fork, most of which is at the southeast corner of the Pulga quadrangle (pl. 1). Its type section, a continuous section through a part of this sequence, is well exposed on roadcuts along the Little North Fork of the Middle Fork of the Feather River (secs. 1, 12, 13, T. 22 N., R. 6 E.). The metamorphic rocks around the Merrimac pluton, which were described earlier (Hietanen, 1951), are included in this formation. The details of their petrography and structure are in the earlier report.

The Horseshoe Bend Formation is separated by faults and metaigneous rocks from the Franklin Canyon and Duffey Dome Formations except on the west side of Granite Basin pluton, where the eastward plunge of the fold axes suggests that it rests on the Duffey Dome Formation. It is thus the youngest formation in the Paleozoic(?) metavolcanic sequence.

The Horseshoe Bend Formation includes layers that are petrologically similar to various layers in the Calaveras Formation, others that are similar to the Franklin Canyon Formation, and still others similar to the Duffey Dome Formation. In addition, there are interbedded layers of metaconglomerate with pebbles of metachert, and layers of bluish-gray quartzite that is different from metachert. Many lens-shaped bodies of marble are included in biotite phyllite. Moreover, there are layers of metalatite very rich in biotite, a rock type not found in the Franklin Canyon Formation.

Several angular fragments of metadiorite, similar to that associated with the metavolcanic rocks of the Franklin Canyon Formation, are included in metadacite exposed in roadcuts at Horseshoe Bend. These inclusions, as well as the conglomerates, suggest that the Horseshoe Bend Formation is probably younger than the Calaveras Formation and younger than the Franklin Canyon Formation. The southeasterly plunges of the fold axes at the headwaters of Marble Creek suggest that the rocks of the Horseshoe Bend Formation rest on the metavolcanic rocks of the Duffey Dome Formation (if beds are right-side up, as indicated on a few outcrops by the relation between cleavage and bedding).

West of Four Trees, however, a fault accompanied by a long body of serpentine separates these two formations. This fault is probably the western extension of the Camel Peak fault, which in the Bucks Lake quadrangle separates the rocks of the Horseshoe Bend Formation from the Franklin Canyon Formation. The metamorphic rocks south of this fault are divided by the Merrimac pluton into two parts that probably belong to the same formation. In each part the older rocks are phyllite with discontinuous layers of quartzite, metachert, and marble. The volume of intermediate metavolcanic rocks is greater in the eastern part of the belt, perhaps owing to a greater part of the strata exposed. In the western part, west of the Merrimac pluton, metabasalt overlies the metasedimentary rocks that near Poe railroad station include discontinuous layers of meta-andesite, metadacite, metarhyolite, and metatuff. A thick layer of conglomerate (or agglomerate?) with meta-andesite pebbles marks the contact between the metasedimentary rocks and overlying metabasalt. Similar metabasalt overlies the interbedded sequence of metasedimentary and intermediate metavolcanic rocks in the easternmost part near Camel Peak (pl. 3).

South of the Pulga quadrangle the Horseshoe Bend Formation is bordered by another fault—the Big Bend fault on plate 3—that extends through Big Bend toward the east and curves around the Bald Rock pluton toward the south. Thus the Horseshoe Bend Formation occupies the innermost southwesterly belt of the Nevadan arcuate segment in which the northerly trends of the Sierra Nevada turn westward.

Distribution of the rock types (particularly the limestone), overturning of folds toward the southwest on the west and southwest sides of the Hartman Bar pluton, and steep dips on the northeast side of this pluton suggest that the major structure in the eastern part of the belt occupied by the rocks of the Horseshoe Bend Formation is a synclinorium into which the Hartman Bar pluton was emplaced. The syncline near Big Bar Mountain and an anticline south of it are the major structures in the western part (see B–B′ on pl. 1). Juxtaposition of structures, such as foliation and lineation, south of Mill Creek is suggestive of a fault between the metabasalt and the metasedimentary rocks to the north, along the Flea Valley Creek near Pulga. This fault seems to continue eastward and could well be concealed by long bodies of talc schist and metagabbro west of the Hartman Bar pluton. Minor displacements were observed on the south side of these bodies.

DESCRIPTION OF THE ROCKS

PHYLLITE

A thick unit consisting of biotite-muscovite phyllite and interbedded quartzite, metachert, and marble borders the Hartman Bar pluton in the northeast and southwest and is in the middle part of the section of the Horseshoe Bend Formation just south of the quadrangle. The phyllite is fine grained and gray to black and consists mainly of quartz, biotite, and muscovite with some magnetite and hematite. A few small crystals of garnet and tiny porphyroblasts of cordierite occur in places; chlorite and some epidote are common along shear zones. The interbedded quartzite layers (1–2 m thick) consist of white to gray micaceous or granular quartzite, in which individual beds are 1–2 cm thick.

Biotite-muscovite phyllite and interbedded metachert exposed on the northwest side of the Merrimac pluton are probably equivalent to this unit. The phyllite here includes layers rich in andalusite and staurolite. Andalusite is in small (1–4 mm long) anhedral light-bluish-gray porphyroblasts that are enveloped by biotite. Thin sections show that anadalusite includes many grains of quartz, biotite, and magnetite (fig. 15). In some porphyroblasts the rows of small inclusions are at an angle to the external foliation, which bends around the porphyroblasts. In a few porphyroblasts the rows of inclusions have an S-shaped curvature, and the outermost part coincides with the external foliation. In some layers several grains include the present foliation. These relations suggest that andalusite started to crystallize early and continued forming during and after the deformation.

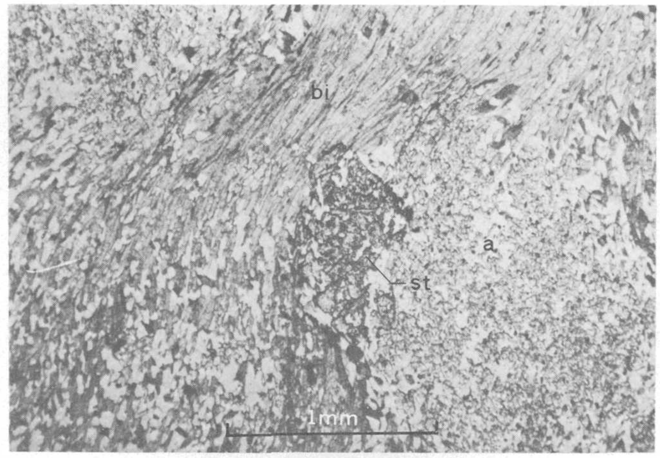


FIGURE 15.—Andalusite (a) and staurolite (st) in biotite (bi) schist of the Horseshoe Bend Formation 1.3 miles east of Big Bar Mountain (loc. 1019). Ordinary light.

Staurolite is in small anhedral to subhedral crystals, 0.2–0.3 mm long, among quartz and biotite or included in andalusite (fig. 15). Foliation bending slightly around the crystals indicates that they are early. (See also Hietanen, 1951, p. 575.) Small euhedral crystals of garnet (0.1–0.2 mm) occur in some layers of biotite phyllite southwest of Coyote Gap (for instance, locs. 989, 1022).

A sequence of metasedimentary rocks that is exposed on either side of Flea Valley Creek near Pulga consists mainly of biotite-muscovite phyllite and chlorite phyllite with interbedded quartzitic and conglomeratic layers and discontinuous layers of limestone and marble. Layers of tuffaceous material metamorphosed to actinolite-epidote-chlorite phyllite and layers of metabasalt are also interbedded. A section through this sequence near Pulga has been described (Hietanen, 1951, fig. 5). A metasedimentary sequence consisting of black phyllite, metachert, and some limestone is well exposed on the railroad cuts near the Poe railroad station and on the road to Bardees Bar in the southwest corner of the Pulga quadrangle and in an area joining it in the south (Hietanen, 1951). Thick beds of agglomerate with some interbedded black phyllite overlie this sequence on the north canyon wall north of Poe and on railroad cuts near Poe. These beds form the lowermost part of the overlying metavolcanic sequence that consists mainly of metabasalt.

Much of the phyllite along Marble Creek is rich in biotite and contains pistachio-green epidote in clusters, small lenses (2–4 cm by 3–15 cm), and veinlike segregations. Layers of biotite phyllite and layers rich in calcite and containing lens-shaped segregations (5–10 cm long) of white calcite are interbedded with epidote phyllite. A sequence of conglomerate, quartzite (1–2 m thick), black phyllite (0.5–1 m), tremolite-biotite quartzite (1–5 m), and phyllite with calcite lenses is repeated several times within a distance of half a mile. This is probably due to the folding on the axis that plunges 55°–60° SE. No folds were observed, but there is a wrinkling around this axis.

MARBLE

The largest exposure of marble is along the Middle Fork of the Feather River. This layer is about 300 m thick and extends from Marble Cone on the north side of the river southward to Hartman Bar Ridge, where it terminates against intrusive tonalite. It is bordered on the west side by this same tonalite and on the east side by dark-gray muscovite-biotite phyllite that contains small garnets. The marble is white and coarse to medium grained and consists almost exclusively of calcite. Numerous large rounded boulders of this marble of ornamental quality occur for half a mile along the river bottom east of Marble Cone. Chemical analysis (table 1) shows that the marble is mainly calcium carbonate, with only half a percent MgO. Magnetite, in very small amounts, is an accessory mineral.

On the eastern part of the occurrence, light-gray oval rings, 1 cm thick and 5 by 10–15 cm in size, are scattered through the snow-white sugary marble. Thin sections show that the gray part contains abundant disseminated magnetite. The regular shape and even thickness of the rings suggest that they are remains of ovoid to kidney-shaped bodies, presumably fossils.

Two thin marble layers separated by phyllite and shown on plate 1 as one layer extend across the river about 1 mile east of Marble Cone. Some beds consist of white marble, but most contain abundant micaceous minerals and grade into calcareous phyllite that contains epidote-rich layers.

Lens-shaped bodies of white to light-gray marble are interbedded with phyllite and quartzite in a northwest-trending zone that extends from the south border of the Bucks Lake quadrangle through Deer Park to Marble Creek in the Pulga quadrangle. Some of these lenses extend for more than 1 mile, but most are only 100–200 m long and a few meters thick. They consist of white calcite with an irregular greenish-gray design of dark minerals—epidote, phlogopite, and pyrite (fig. 16). Biotite phyllite near the marble contains abundant calcite, albite, epidote, and pyrite. Calcite and albite are segregated into small lenslike and layerlike masses that are embedded in biotite-epidote-quartz-albite phyllite.

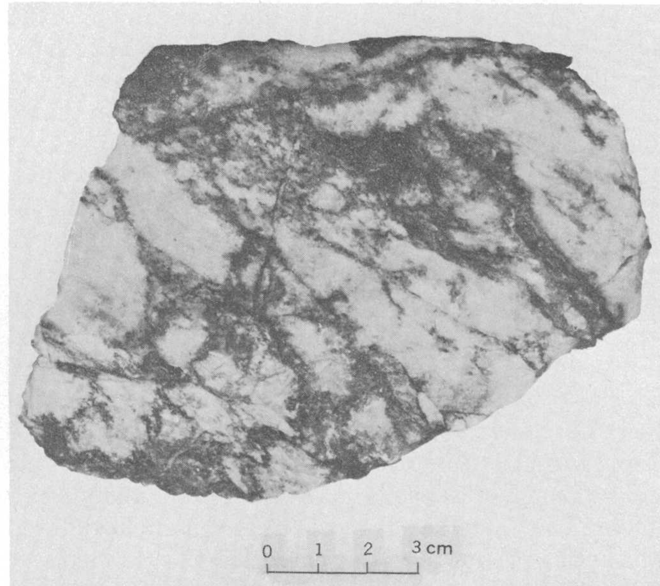


FIGURE 16.—Marble from the Horseshoe Bend Formation on the Little North Fork of the Middle Fork of the Feather River 0.2 mile northwest of the mouth of Glazer Creek. The white parts are calcite; dark material is epidote, phlogopite, and pyrite.

Several thin layers of marble are interbedded with phyllite, quartzite, and hornblende gneiss (metatuff) north of Pulga. About 300 and 400 m north of Pulga, small lenses of white calcite are embedded in light-gray micaceous and calcareous phyllite. A layer half a mile to the north is 1 m thick and consists of white marble. The layer exposed just north of Flea Valley Creek continues about 0.6 miles to the west and consists of very light gray calcium carbonate with some pyrite and muscovite, occasional diopside, and actinolitic hornblende. This layer is underlain by thin-bedded gray quartzite and overlain by hornblende gneiss (metatuff).

QUARTZITE

Most of the quartzite in the Horseshoe Bend Formation is light gray to white and granular. Some of it is thin bedded and resembles metachert, but bedding typical of clastic sediments (sands and tuffs) can be detected in many other places. Several layers of white granular quartzite are interbedded with phyllite on Rock Island Ridge. Phyllite near these layers contains lenses of similar quartzite. On the south side of Bear Gulch, a thick layer of white granular quartzite is exposed just north of metadacite and metarhyolite (pl. 2). This quartzite extends to the quadrangle border in the southeast and to Marble Creek in the northwest. It is in part thin bedded and rich in muscovite; in some thicker layers micaceous minerals are scarce. On the higher slope on the south side of Bear Gulch, some layers of thin-bedded (3–5 cm) white quartzite have irregular bedding that gives a lenticular appearance to the quartzite. In these layers small lenses of granular quartzite are enveloped by muscovite laminae.

At the road junction to the Bear Ranch Hill, a layer of bluish-gray quartzite crops out just south of bluish-gray metarhyolite. The quartzite is granular and lacks the type of bedding characteristic of metacherts. This quartzite continues to the southwest and is well exposed north of the Silver Crescent mine. It is in part thin bedded (1–10 mm), but also includes thick beds (20 cm–1 m) and grades to metarhyolite in the northwest. Discontinuous layers of similar gray to white granular quartzite are interbedded with metavolcanic rocks of the Horseshoe Bend Formation in many other places. This quartzite is most likely a metamorphosed weathering product of silicic volcanic rocks, particularly of rhyolitic tuff.

CONGLOMERATE

Conglomerate and pebbly layers are common in quartzite exposed in the upper drainage of Marble Creek and for a distance 1½ miles westward from Four Trees. The pebbles consist of light-gray to white granular quartzite, presumably metachert. They are embedded in a fine-grained medium-gray dense matrix and are flattened in the plane of foliation. Similar pebbles are embedded in some layers of phyllite. The matrix in most layers is micaceous, but in some it contains actinolite and epidote.

METAVOLCANIC LAYERS

The meta-andesite and metadacite of the Horseshoe Bend Formation are petrographically similar to the corresponding rocks in the Franklin Canyon Formation. Metabasalt is well foliated and mineralogically similar to the metabasalt in the Duffey Dome Formation. Blue-green hornblende in typical dark metabasalt, such as that exposed on the road to Sky High in the southwest corner of the Bucks Lake quadrangle (loc. 241), shows $\gamma=1.693\pm0.002$, $\beta=1.668\pm0.002$, and $Z \wedge c=18°$. In some lighter colored layers hornblende is very pale green and has $\gamma=1.681\pm0.002$ (loc. 243).

Metalatite exposed on the Little North Fork of the Middle Fork of Feather River (loc. 856) is brownish gray and crudely foliated and contains biotite that can be readily identified in the field. Thin sections show that biotite occurs in large flakes and clusters that represent former phenocrysts. Phenocrysts of quartz are granulated, and phenocrysts of albite include many small flakes of muscovite, chlorite, and epidote. The groundmass consists of quartz, albite, epidote, chlorite, muscovite, biotite, and magnetite.

Metatuff of latitic composition occurs as thin layers along the Little North Fork. These layers consist of quartz, albite, muscovite, and biotite with some chlorite, ilmenite-magnetite, sphene, and pyrite. Small phenocrysts of quartz and albite are common. Metatuff occurring with meta-andesite and metadacite contains abundant actinolite and at most only a small amount of biotite and muscovite.

The thin discontinuous layers of metarhyolite occurring with metadacite along the Little North Fork of the Middle Fork of the Feather River contain very little if any potassium feldspar and are most likely silica-rich differentiates of dacitic magma. In contrast to these, the thin layer of metarhyolite exposed on Marble Creek (loc. 1256) is rich in potassium feldspar. The possibility that this body is a dike cannot be ruled out.

TENTATIVE CORRELATION OF METAMORPHIC ROCKS SOUTHWEST OF MELONES FAULT

The continuity of the outcrops of the metamorphic rocks south of the area is interrupted by Cenozoic volcanic rocks that cover higher elevations on ridges south of the Bucks Lake quadrangle. The older rocks are, however, exposed at lower elevations in the deep canyons of the South Fork of the Feather River and its tributaries and seem to continue southward parallel to the regional trend. On the geologic map of the Chico sheet (Burnett and Jennings, 1962), a part of the metavolcanic rocks south of the Cenozoic cover is shown as Mesozoic and the other part as Paleozoic. All these rocks are probably of Paleozoic age because the succession of lithologic units in the Bucks Lake quadrangle is in a general way similar to the Paleozoic section along the North Fork of the Yuba River as described by Ferguson and Gannett (1932).

Farther south, just north of the 39th parallel, Chandra (1961) described in detail a Paleozoic section west of the Melones fault and correlated the pyroclastic rocks with the Mississippian Tightner Formation of Ferguson and Gannett (1932). This formation includes meta-andesite and metadacite, whereas metabasalt is included by Chandra in the overlying Cape Horn Slate, which is in turn overlain by a heterogeneous succession of metasedimentary rocks including conglomerate, phyllite, metachert, quartzite, and limestone. In general this succession is similar to the pyroclastic sequence—the Franklin Canyon and Duffey Dome Formations and the overlying Horseshoe Bend Formation in the Pulga and Bucks Lake quadrangles.

Correlation across the serpentine belt to the Paleozoic formations on the east side of the Melones fault is even more uncertain. Nevertheless, the sections through the Calaveras Formation around the 38th parallel (Clark, 1964) include a pyroclastic unit that could be broadly equivalent to the pyroclastic sequence of this report.

Comparison of the succession of lithologic units in the Pulga and Bucks Lake quadrangles with that in the neighboring Taylorsville area as described by McMath (1966) indicates that the following correlations are possible:

1. The blastoclastic quartzite and interbedded muscovite phyllite around Snake Lake in the northeast corner of the Bucks Lake quadrangle are probably equivalent to the middle part of the Shoo Fly Formation.
2. The interbedded metachert and phyllite southwest of the Rich Bar fault—the Calaveras Formation of this report—may be equivalent to parts of the Shoo Fly Formation elsewhere.
3. The metavolcanic sequence, which overlies the rocks of the Calaveras Formation, may include units equivalent to petrologically similar units in the pyroclastic sequence of the Taylorsville area. Specifically, the metadacite and metamorphosed sodarhyolite of the Franklin Canyon Formation may be broadly equivalent to the Sierra Buttes Formation of McMath (1966) in the Taylorsville area. The meta-andesite on the Dogwood Peak and that northeast of Silver Lake could be equivalent to the Taylor Meta-andesite.
4. Assuming widespread volcanism of the same type, the metarhyolite and metabasalt of the Duffey Dome Formation could have been laid down contemporaneously with the Mississippian Peale and Goodhue Formations of McMath (1966) in Taylorsville area.

The Horseshoe Bend Formation, which overlies the Duffey Dome Formation at the headwaters of Marble Creek and is separated from the Franklin Canyon Formation by a belt of ultrabasic rocks in the southern part of the Bucks Lake quadrangle and in the area to the south (in the American House quadrangle), includes units lithologically similar to the Permian Reeve and Robinson Formations. The Reeve Meta-andesite of the Tayorsville area consists of keratophyre breccia and tuff, fusulinid limestone, and chert-pebble conglomerate. The sequence of metadacite, metarhyolite, metatuff, phyllite, quartzite, metachert-pebble conglomerate, and marble exposed along Marble Creek and along the Middle Fork and the South Branch of the Middle Fork of the Feather River south of the Bucks Lake quadrangle could be equivalent to this formation. No positive identification of fossil remains could be made because of profound deformation and recrystallization. Textures reminiscent of fossils were observed in some thin sections of carbonate-rich layers. Tiny waterworn cavities form spirals on the surfaces of some small calcite-quartz aggregates embedded in black phyllite in the streambed of the South Branch of the Middle Fork of the Feather River about 0.7 mile south of the Bucks Lake quadrangle. These aggregates, 1–3 cm long and ½–2 cm thick, are flattened in the plane of foliation and recrystallized to the extent that identification of the original fossils is impossible.

CEDAR FORMATION

Muscovite slate in a small wedge-shaped area on the north border of the Bucks Lake quadrangle just east of the Melones fault is shown as the Cedar Formation on the Bidwell Bar map (Turner, 1898). This formation has been dated as Triassic by McMath (1958) in the area north of the quadrangle, where it includes fossiliferous limestone beds, and Permo(?)-Triassic by Moores (1970). The east boundary in the Bucks Lake quadrangle is marked by a juxtaposition of structures along a shear zone and thus may be a fault.

The slate is light beige and fine grained. Only the plane of foliation can be measured in most outcrops; some show isoclinal folding and axial plane cleavage. Farther to the north, on the East Branch of the North Fork of the Feather River, this formation consists of muscovite-chlorite phyllite with interbedded layers of black limestone.

METAMORPHOSED INTRUSIVE ROCKS

Two large and several small bodies of ultramafic rocks — peridotite, olivinite and pyroxenite — partly altered to serpentine, soapstone, and talc schist were emplaced at an early date and were deformed with the metamorphic rocks. Small bodies of pyroxenite (mostly altered to hornblendite), metagabbro, metamorphosed quartz diorite, and metatrondhjemite were intruded into the volcanic rocks and were recrystallized with them. These metamorphosed intrusive rocks probably are deep-seated equivalents of the chemically similar metavolcanic rocks. Dikelike bodies of meta-andesite and metamorphosed quartz porphyry cut the metasedimentary and metavolcanic rocks.

ULTRAMAFIC ROCKS

The continuous belt of ultramafic rocks in the northeastern part of the area is bordered by high-angle faults on either side—the Melones fault on the northeast and the Rich Bar fault on the southwest. Smaller masses elsewhere resemble sills or dikes, many of which were emplaced in tectonically suitable places as along faults or in tectonic low-pressure areas, such as fold apices (south of Big Bar Mountain and east of Rocky Ridge in the Pulga quadrangle; Coyote Gap and northwest of

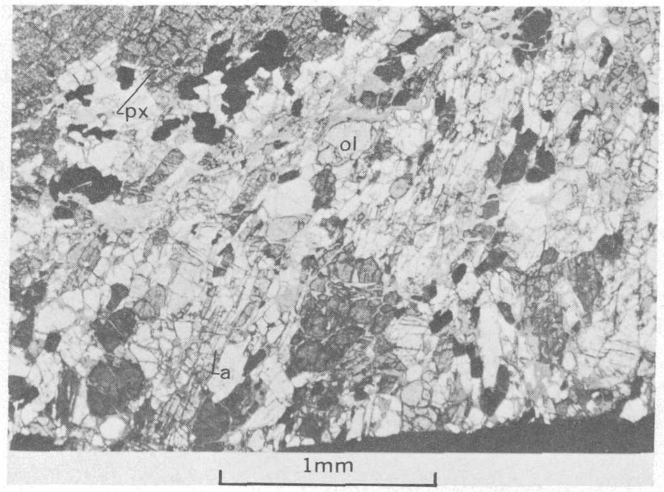
Hartman Bar in the Bucks Lake quadrangle). A mass on Oak Ridge fills the triangular area between the plutons and was probably deformed by them.

Most of the ultramafic rocks are dense dark-green rocks that either weather to a rusty color or break into blocks with shiny green slickensides. All degrees of serpentinization of the primary constituents — olivine, pyroxene, and amphibole—occur within large masses, as well as further alteration to antigorite-carbonate rock, talc-carbonate rock, and talc schist. The outermost layer commonly consists of talc schist and is separated from the surrounding metasedimentary or metavolcanic rock by a layer of tremolite rock. Most of the small masses are talc schist.

Thin sections show that the primary minerals are well preserved in the central parts of the two largest masses in the Bucks Lake quadrangle. The estimated percentages of the major constituents—olivine 50–70, pyroxene 10–30, amphibole 10–20, magnetite and chromite 1–2—indicate according to Johannsen's classification (1951) that they are hornblende-pyroxene olivinite and peridotite. Both clinopyroxene and orthopyroxene are common. Amphibole is very weakly pleochroic (γ=very light beige, $\alpha=\beta$=colorless) to colorless; its $Z \wedge c=17°–21°$, and $-2V$ is large. Very thin (0.005–0.002 mm) seams of serpentine minerals, mainly chrysotile, occur along fractures in the grains and around grain boundaries (fig. 17). Many seams transect the grain boundaries and occur equally in olivine, pyroxene, and amphibole. This, together with the texture, proves that the amphibole is primary. Where serpentinization has advanced farther, the seams are wider and consist of a fine-grained mesh of serpentine minerals that give chrysotile and lizardite X-ray powder patterns. (See Whittaker and Zussman, 1956.)

Chemical analyses of the hornblende-pyroxene olivinite exposed on Meadow Valley Creek (loc. 134) are shown in table 1. The primary minerals, olivine, pyroxene, and amphibole, were separated from this rock and also analyzed. The calculated formulas and percentage of end members are shown with the analyses and the trace element contents in table 2. Olivine is forsterite with only 10 percent fayalite. Pyroxene is entatite that contains 9 percent ferrosilite and very little calcium and aluminum, which were calculated as Tschermak's molecule, $CaAl_2SiO_6$. The calculation of the formula of the primary amphibole indicates that it is a magnesium-rich hornblende with 1.2 Al substituting for Si. It differs from common igneous hornblende mainly because of exceptionally high magnesium and low iron and calcium contents.

The distribution of [Mg/Fe] between olivine and enstatite is about equal (fig. 18), but because of much larger [Mg/Fe] in hornblende, the distribution coefficient, K_D [Mg/Fe], for En/Ho=0.694 and for Ol/Ho =0.712.



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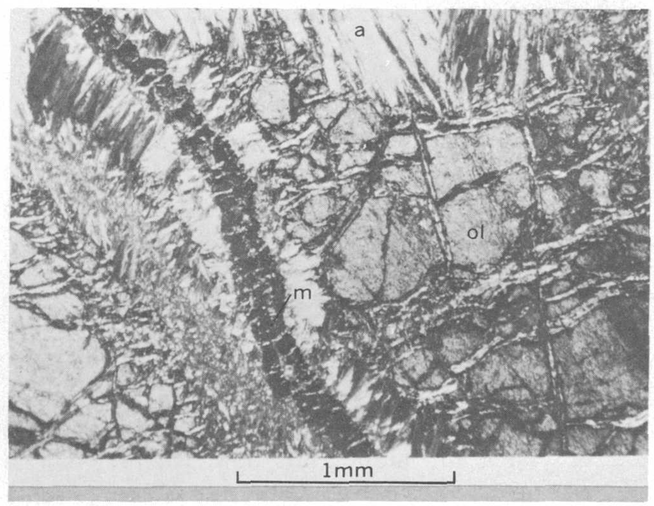

B

FIGURE 17.—Photomicrographs of altered peridotite. *A*. Chrysotile along minute fractures and grain boundaries in olivine (ol), pyroxene (px), and amphibole (a). Hornblende-pyroxene olvinite at Meadow Valley Creek (loc. 134). Crossed nicols. *B*, Early irregular small fractures in olivine (ol) are filled by chrysotile; the wide fractures parallel to the cross joints are filled by magnesite (m) and antigorite (a). Peridotite 1 mile southeast of Frenchman Hill (loc. 783). Crossed nicols.

Comparison with experimental work and with other Alpine-type peridotites (Medaris, 1969) shows that the distribution of [Fe/Mg] between olivine and enstatite in sample 134 is similar to that in the experimental work at 900°C and to that in the Alpine peridotites. Medaris also pointed out that distribution does not change between 900° and 1,300°C and cannot be used as a geologic thermometer. Rather the only conclusion that

TABLE 2.—*Chemical composition, calculated formulas, and trace elements of blue-green hornblende from metagabbro (specimen 796) and magnesian hornblende, enstatite, and olivine from peridotite (specimen 134), Bucks Lake quadrangle*

[Data for chemical composition by C. O. Ingamells, project leader; N. H. Suhr, Penn. State Univ., determined by emission spectrometry in samples from peridotite (specimen 134) the following: SiO_2, Al_2O_3, MgO, CrO, TiO_2, MnO, Cr_2O_3, NiO, BaO, SrO. Trace elements determined from spectographic analyses by R. E. Mays, except Ba, Y, and Yb which were analyzed by Chris Heropoulos]

	796—h		134—h		134—e		134—o	
	Blue-green hornblende		Magnesian hornblende		Enstatite		Olivine	
	Weight percent	Molecular equivalent	Weight percent	Molecular equivalent	Weight percent	Molecular equivalent	Weight percent	Molecular equivalent
Chemical composition								
SiO_2	43.63	7263	49.0	8153	53.0	8819	41.0	6822
Al_2O_3	14.47	1419	7.4	726	1.52	149	.10	10
Cr_2O_3[2]	.05	3	.67	44	.24	16	....	....
Fe_2O_3	3.70	232	.9	56	.20	13	1.7	107
FeO	7.69	1070	2.91	405	6.31	878	8.25	1148
MnO	.15	21	.10	14	.17	24	.16	23
NiO	....	....	.08	10	.07	9	.30	40
MgO	13.04	3234	23.8	5903	35.8	8879	48.6	12054
TiO_2	.21	26	.22	27	.05	6	....	....
P_2O_5	....	....	<.01	....	<.01	....	<.01	....
V_2O_5[2]	.04	3	....	....	....	....	....	....
CaO	12.23	2180	11.3	2015	1.14	203	.13	23
BaO	....	....	<.01	....	<.01	....	<.01	....
SrO	....	....	<.01	....	<.01	....	<.01	....
Na_2O	1.90	307	1.10	177	.13	21	.00	....
K_2O	.23	24	.09	10	.02	2	.002	....
F	.02	11	....	....	....	....	....	....
H_2O^+	1.8	999	2.9	1610	1.5	833	.25	139
H_2O^-	....	....	....	....	....	....	....	....
Total	99.16		100.5					
Number of ions in a unit cell								
Si	6.36		6.75		1.88		1.00	
Al	1.64		1.20		.06		....	
Cr	....		.05		.01		....	
Tetrahedral Σ =	8.00		8.00		1.95		1.00	
Al	0.85		....		....		....	
Cr	.01		0.02		....		....	
Fe^{3+}	.41		.09		....		0.03	
Ti	.02		.02		....		....	
V	.01		....		....		....	
Ni	....		.01		....		.01	
Mg	2.83		4.89		1.89		1.77	
Fe^{2+}	.87		....		.19		.17	
Mn	....		....		....		....	
M(1)–M(3) Σ =	5.00		5.03		....		....	
Fe^{2+}	0.07		0.34		....		....	
Mn	.02		.01		....		....	
Ca	1.91		1.65		.04		....	
M(4) Σ =	2.00		2.00		2.12		1.98	
					Percentage of end members			
Ca	....		0.02		Enstatite 89.15		Forsterite 89.9	
Na	0.54		.29		Ferrosilite 8.96		Fayalite 10.1	
K	.04		.02		Tschermak's mol... 1.89			
A-site Σ =	0.58		0.33					
OH	1.75		2.67					
F	.01		....					
	1.76		2.67					
	Mg/Fe = 3.01		Mg/Fe = 14.38		Mg/Fe = 9.95		Mg/Fe = 10.4	
	Al/Mg = 0.88		Al/Mg = 0.25					
	α = 1.651		α = 1.622		α = 1.662		α = 1.653	
	β = 1.662		β = 1.630		β = 1.666		β = 1.670	
	γ = 1.671		γ = 1.641		γ = 1.671		γ = 1.688	
Trace elements, in parts per million								
Ba	5		16		<4		<4	
Be	0		<2		<2		<2	
Co	38		24		60		160	
Cr	350		6,000		1,600		50	
Cu	22		44		13		9	
Ga	20		<7		<7		<7	
Ni	70		600		600		2,100	
Se	90		60		<10		<10	
Sr	8		28		<4		<4	
V	210		290		60		<4	
Y	10		20		<20		<20	
Yb	1		2		<2		<2	
Zr	7		20		<20		<20	

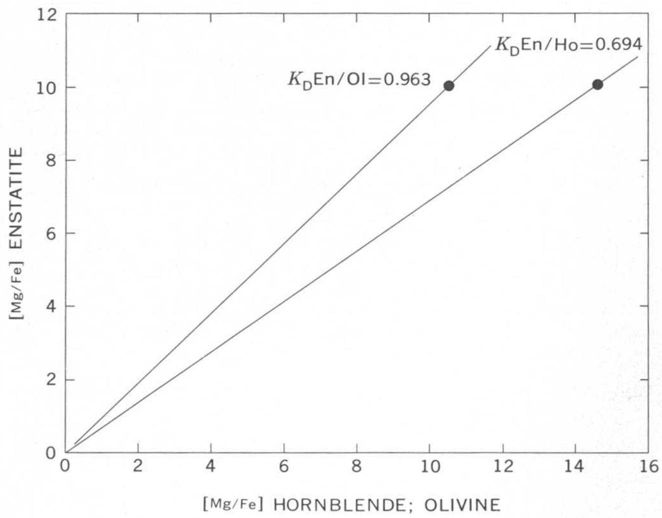

FIGURE 18.—Distribution of [Mg/Fe] between enstatite, olivine, and hornblende in olivinite No. 134 (table 1).

can be made on the basis of similarity of distribution in the natural occurrences and in the experimental work is that these minerals crystallized in equilibrium also in the natural occurrence.

Comparison of the trace element content of the analyzed olivine, enstatite, and hornblende with that of their host rock (table 5, No. 134) shows that most of the chromium and vanadium are in the amphibole, whereas nickel and cobalt are concentrated in olivine. The concentration of copper in the host rock is higher than in the analyzed minerals, indicating that the opaque minerals contain copper.

The large ultramafic mass south of Bucks Lake shows every stage of serpentinization and steatitization from olivinite that is only about 20 percent serpentinized through serpentine-talc-carbonate rock to soapstone with appreciable carbonate content or to talc schist. The rock around Frenchman Hill consists of olivinite and dunite that weathers rusty red. The dunite has two sets of fractures. The earlier ones that are seen in thin sections as irregular or subparallel fractures, 0.01–0.02 mm wide, may lend a very slight irregular foliation to the rock in outcrop. These tiny fractures are filled by fibrous serpentine minerals, probably chrysotile. Fibers are elongate perpendicular to the walls of the fractures. Another set of fractures is throughgoing and measurable in the field. These fractures are 0.5–1 mm wide and transect the rock at 0.5–3-cm intervals. They are approximately perpendicular to the regional fold axes and thus are most likely tension fractures. These tectonic fractures are filled by magnesite and antigorite; the magnesite is in the center, and laths of antigorite radiate from it or are perpendicular to it (fig. 17). The laths of antigorite penetrate deep into olivine crystals, and in places clusters of antigorite replace olivine a short distance outside the cross joint fracture.

In the advanced stages of serpentinization and steatitization toward the borders of the masses, the alterations have advanced from wide throughgoing fractures (1–4 cm wide) into the host rock in an irregular manner, producing patches that consist of antigorite and carbonate or of talc, antigorite, and carbonate. Pyroxene is the first mineral to be replaced by carbonate and antigorite. Relict outlines and cleavage of former pyroxene are seen as segregations of tiny grains of magnetite deposited along these planes during the first stage of serpentinization. At the second stage only a part of the olivine is replaced by antigorite. In places, as in location 171 (pl. 2), chrysotile and lizardite persist after a considerable amount of antigorite and carbonate are formed. At these places, serpentinization had proceeded farther before the formation of carbonate and antigorite began.

Near Grizzly Mountain and to the southeast, talc appears first along fractures and then as clusters with carbonate (fig. 19). Toward the south and southeast border zones of the mass, talc is a major constituent. A part of the border zones consists of talc schist or of talc-carbonate and antigorite-carbonate rock, and another part of antigorite-talc-carbonate and talc-antigorite rock. Specular hematite and chromite are common accessory minerals in the antigorite-talc-carbonate rock.

All the ultramafic rock on Soapstone Hill has altered to soapstone that consists of talc, carbonate, and antigorite in varying amounts. Relict textures seen in thin section are similar to those in partly steatitized rocks on Grizzly Mountain; thus perhaps the origin and his-

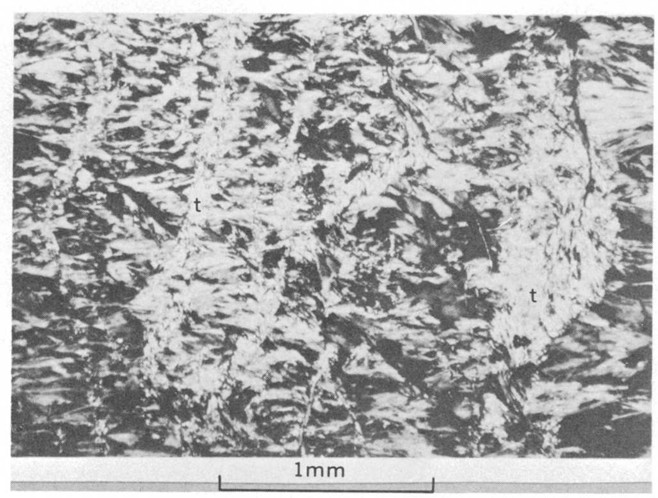

FIGURE 19.—Seams of talc (t) in antigorite serpentine at the east border of the ultramafic mass south of Bucks Lake (loc. 73). Crossed nicols.

tory of alteration are also similar. Magnetite in the soapstone is crystallized as anhedral to subhedral grains and clusters. Carbonate fills fractures and occurs in many places as rhombic crystals.

Many contact zones between the ultramafic rocks and the metasedimentary or metavolcanic rocks consist of tremolite or of talc-tremolite rock, indicating outward migration of calcium and magnesium from the serpentinized peridotite. Abundant tremolite-actinolite also occurs in the wallrock next to the contact. The thickness of the tremolite-rich layer ranges from about 10 cm to several meters. The tremolite needles are light to medium green, commonly larger than the other minerals, talc and antigorite, and are subparallel to the contact or oriented at random.

Chemical reactions leading to these various stages of serpentinization and steatitization of the hornblende-pyroxene olivinites can be summarized as follows:

1. The primary minerals—olivine, pyroxene, and amphibole — underwent minor serpentinization along irregular fractures. The small amount of H_2O needed may have been in a magmatic rest solution in the intergranular cavities of the ultramafic rock during the latest phase of intrusion. The serpentine minerals formed were chrysotile and lizardite. The qualitative reactions can be expressed as

$$3MgSiO_3 + 2H_2O \rightarrow Mg_3(OH)_4Si_2O_5 + SiO_2$$
3 enstatite + 2 water → serpentine + silica,

$$3Mg_7(OH)_2Si_8O_{22} + 11H_2O \rightarrow 7Mg_3(OH)_4Si_2O_5 + 10SiO_2$$
3 cummingtonite + 11 water → 7 serpentine + 10 silica,

$$3Mg_2SiO_4 + SiO_2 + 4H_2O \rightarrow 2Mg_3(OH)_4Si_2O_5$$
3 olivine + silica + 4 water → 2 serpentine.

The silica released in the first and second reactions was subsequently used in the third reaction. Some magnetite was precipitated with the serpentine minerals along the fractures. Where amphibole is primary, as in the analyzed specimen (No. 134, table 2), hydrogrossular may have crystallized from the calcium and aluminum contained in the amphibole.

2. Magnesite and antigorite crystallized along later, wide fractures as a result of introduction of CO_2 and H_2O, presumably from the surrounding sedimentary rocks, which would have released CO_2 and H_2O during the first episode of metamorphism. The structural control of the fracture system near Frenchman Hill suggests that these fractures were formed during deformation. Since the regional metamorphism was syntectonic, the crystallization of antigorite and magnesite occurred during this first period of metamorphism. The silica needed for formation of antigorite from olivine was released according to the reaction

$$Mg_2SiO_4 + 2CO_2 \rightarrow 2MgCO_3 + SiO_2$$
olivine + 2 carbon dioxide → 2 magnesite + silica.

3. Crystallization of talc in addition to antigorite and magnesite required an addition of silica from outside. This reaction is far more common in thin bodies that were strongly deformed by tectonic movements than in large masses. In the thin layers of talc schist, the foliation and lineation are parallel to the corresponding structures in the enveloping metamorphic rocks, indicating that the talc was crystallized during the deformation. Talc was formed in outer zones of the masses essentially during the same phase as antigorite and carbonate in the inner zones, but the front of introduced silica lagged behind that of CO_2 and H_2O. Not all olivine was first serpentinized and then altered to talc. Thin sections show a considerable amount of olivine in the rocks in which talc replaces primary minerals. Thus the reaction occurred only where enough silica was available and is expressed as

$$3Mg_2SiO_4 + 5SiO_2 + 2H_2O \rightarrow 2Mg_3(OH)_2Si_4O_{10}$$
olivine + 5 silica + 2 water → 2 talc

or

$$3MgSiO_3 + SiO_2 + H_2O \rightarrow Mg_3(OH)_2Si_4O_{10}$$
enstatite + silica + water → talc.

4. Crystallization of abundant tremolite along the contact zones of the ultramafic masses indicates that calcium, which was released during the serpentinization and steatitization of amphibole and pyroxene, migrated outward and was combined with outward-migrating magnesium and with silica of the wallrock to form tremolite as

$$2CaO + 5MgO + 8SiO_2 + H_2O \rightarrow Ca_2Mg_5(OH)_2Si_8O_{22}$$
(from peridotite) (from wallrock) → tremolite.

Some of the tremolite in the ultramafic mass, which was earlier altered to talc-carbonate rock, was formed during the second episode of metamorphism as

$$Mg_3(OH)_2Si_4O_{10} + 2CaMg(CO_3)_2 + 4SiO_2 \rightarrow Ca_2Mg_5(OH)_2Si_8O_{22} + 4CO_2$$
Talc + 2 dolomite + 4 silica → tremolite.

This reaction occurred at the temperatures of the epidote-amphibolite facies.

Exchange of elements during the serpentinization is thus essentially similar to that described from many other areas (Thayer, 1966; Page, 1967; Cerny, 1968); that is, water migrated into the ultramafic mass, and calcium and magnesium moved out. The volume increased, but this was due mainly to tectonism, as shown by the fact that serpentinization started along the expansion cracks that parallel the cross joints. Thus the shearing, crushing, and other tectonic effects may

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have greatly facilitated serpentinization by making the ultramafic mass accessible to H_2O and CO_2, which were expelled from the surrounding rocks during this same phase of regional metamorphism.

The mineralogy of the serpentinized peridotite in the northern part of the Bucks Lake quadrangle differs somewhat from that just described; chrysotile and lizardite make up most of the rock, in which relict olivine is surrounded by a corona of fibrous pyroxene. Similar pyroxene with $Z \wedge c=36°–40°$ surrounds spots of serpentine minerals with secondary magnetite, which originally precipitated along fractures in former olivine. Large grains of primary pyroxene in this rock have altered to a mixture consisting of cummingtonitic amphibole ($Z \wedge c=13°$) and hydrogrossular. Several large grains of hydrogrossular replacing olivine occur in locality 395. Most of the long amphibole (anthophyllite?) prisms, which in locality 385 transect the serpentine, are altered to chrysotile and lizardite still preserving the parallel extinction. This amphibole is later than the first stage of serpentinization. The sequence of events was as follows:

1. Partial serpentinization of olivine, primary pyroxene, and primary amphibole accompanied by precipitation of magnetite along the fractures.
2. Continued serpentinization accompanied by crystallization of secondary amphibole, hydrogrossular, and chlorite.
3. In places serpentinization of secondary amphibole and crystallization of chlorite.

Formation of chlorite is especially common near fault zones.

Most of the small ultramafic bodies consisted originally of peridotite with a higher percentage of pyroxene than is present in the two largest masses just described. In some small bodies, peridotite is altered to amphibole-serpentine rock, as seen for example in small ultramafic bodies exposed in localities 466 and 62. In locality 466, pyroxene was originally the major rock constituent (70–90 percent) and occurred in large crystals that included small olivine crystals. Pyroxene, some still showing subhedral outlines, is altered to light-green to colorless amphibole and olivine to serpentine, talc, and colorless amphibole. Chrysotile and magnetite occur along the relict cracks of former olivine.

A serpentinized part of a long thin ultramafic body along the north border of T. 22 N., R. 7 E., consisted originally of about 70 percent pyroxene and 30 percent olivine. The relict cleavage of pyroxene and relict cracks of olivine are indicated by magnetite that precipitated along these surfaces at an early stage of serpentinization. Olivine was first altered to chrysotile along cracks, and the rest of this mineral was later altered to talc and serpentine minerals, mainly antigorite. Pyroxene was altered first to amphibole, and aggregates of antigorite then developed within the large amphibole crystals, replacing about 50 percent of the original volume of the amphibole. Wide seams of chrysotile-type serpentine with magnetite in their central parts transect this rock, which now consists of about 30 percent amphibole, 60 percent serpentine minerals, and 10 percent talc.

A small body of altered pyroxenite extends for more than 1 mile from the south slope of Frazer Hill (loc. 550) toward the southeast. Thin sections show relict prophyritic texture. The large (1–3 mm long) phenocrysts of pyroxene now consist of several smaller clinopyroxene crystals that show $Z \wedge c \sim 35°$ and $+ 2V \sim 60°$ and are partly altered to tremolite. The fine-grained groundmass contains numerous medium-size (0.1–0.2 mm) crystals of pyroxene, many of which are euhedral and partly altered to amphibole. Alteration to amphibole is highly irregular, proceeding along fractures and forming patches in the groundmass and within larger pyroxene crystals. The fine-grained granoblastic groundmass consists of about 40 percent pyroxene and 60 percent amphibole. Tiny grains of magnetite are included in pyroxene, primarily along its cleavage. Where amphibole is the major constituent, magnetite forms somewhat larger, scattered grains.

A part of the long thin ultramafic body along the north border of T. 22 N., R. 7 E., consists of pyroxenite that has been partly altered to amphibole rock, with further partial alteration to antigorite and very little talc and carbonate. The pyroxenite is coarse grained and consists of about 70 percent clinopyroxene. Alteration to amphibole is mainly along the cracks and grain boundaries, whereas antigorite and talc form small patches and occur along fractures and shear zones.

Thus the original composition of ultramafic rocks ranged from dunite and olivinite to peridotite and pyroxenite. Chemical analysis of a representative sample of olivinite (No. 134, table 1) shows that these rocks are rich in magnesium, and thereby they differ strikingly from the members of the other igneous rocks series in this region. (See fig. 39.) They are typical representatives of Alpine-type peridotite-serpentine masses that were emplaced along fault zones in a cool and mainly solid state. The high-temperature contact aureoles are absent, and microbrecciation is ubiquitous. The early serpentine minerals that fill the interstices and the tiny cracks formed by microbrecciation probably represent the only liquid contained in the ultramafic crystal accumulate during its ascent from a deep-seated magma chamber or from the mantle.

ROCKS ASSOCIATED WITH SERPENTINES

Several small masses consisting of albite or albitic oligoclase with some actinolitic hornblende, muscovite, and rarely corundum occur within the serpentines.

Some of these are dikes with fine-grained borders; the others are coarse-grained masses similar to albitites. A dike consisting of oligoclase and corundum was described by Lawson (1903) under the name of plumasite. Crystals of axinite, small masses of vesuvianite, and a dikelike body consisting of rodingitelike rock occur near Pulga.

Four small masses of coarse-grained albitite cut the serpentine. Two of these—both hornblende bearing—are along the Melones fault (locs. 290, 400); the third one, a muscovite albitite, is a north-trending dike on the north slope of Grizzly Mountain (loc. 172); and the fourth mass is north of Pulga (loc. 1263).

The albitite at locality 290 is dark bluish gray and consists mainly of albite with some quartz, hornblende, chlorite, calcite, zoisite, and epidote. Albite (An_3) constitutes 95 percent of the light-colored parts of the outcrops. It occurs in anhedral grains that are 1–3 mm in diameter and have irregular outlines. Actinolitic hornblende is segregated in layerlike bodies.

Albitite at locality 400 has elongate clusters of large (0.5 mm) grains of quartz, subhedral crystals of albite, and trains of bluish-green hornblende in a mosaic of small (0.1 mm) grains of quartz and albite. Crystals of hornblende are rimmed by needles of actinolite. Ilmenite-magnetite surrounded by sphene occurs as an accessory mineral.

The muscovite albitite at Grizzly Mountain is light tan and coarse grained. Albite is in anhedral grains 1–2 mm in diameter. Most of the quartz is in anhedral grains; some grains are bounded by crystal faces. Large flakes (1–2 mm long) of muscovite are in radiating clusters, and numerous tiny flakes are included in albite. There are small grains of accessory magnetite.

A fine-grained quartz porphyry dike cuts serpentine on a low ridge 1.7 miles east of Spanish Peak (loc. 1044) northeast of the locality in which Lawson (1903) described a dike of coarse-grained oligoclase-corundum rock (plumasite) with fine-grained or porphyritic borders. Phenocrysts in the fine-grained dike are quartz and albitic plagioclase; the groundmass consists of quartz, albitic plagioclase, and biotite. Tiny crystals of corundum and magnetite occur as accessory minerals. Blocks of coarse-grained white rock found in an old digging just south of the dike consist of 98 percent oligoclase (An_{15}) with very little actinolite, muscovite, chlorite, and a few small grains of quartz. These blocks probably were left after corundum-bearing rock was quarried out.

Brown crystals of axinite occur with quartz in veinlike masses cutting the meta-andesite just west of the serpentine near locality 1044 in secs. 16 and 21, T. 24 N., R. 8 E. The meta-andesite contains tiny phenocrysts of albite in a groundmass of actinolite, epidote, and albite; round vesicles are filled by quartz and epidote.

A specimen showing the contact of the meta-andesite and quartz-axinite vein was received from A. Pabst, University of California at Berkeley. Microscopic examination of this specimen shows that small angular inclusions of meta-andesite, some partly digested, occur in this vein near its walls and that hairlike tremolite extends from the wallrock into the vein quartz and is partly included also in the axinite. Axinite occurs in subhedral large crystals that show $\alpha=1.671\pm0.001$, $\beta=1.676\pm0.001$, $\gamma=1.682\pm0.001$, and $-2V=82°$.

Vesuvianite that occurs as small masses in serpentine and talc schist is fine grained, apple green, and translucent. A layerlike body of gray-green massive rock consisting of fine-grained gray-green vesuvianite, with epidote, oligoclase, tremolite, grossularite and calcite, is exposed at the 2,200-foot elevation north of Pulga. This mass is similar in its mineralogy and mode of occurrence to rodingite and may have a similar origin, representing segregation of calcium released from pyroxene of the ultramafic rock during its serpentinization.

Small masses of fibrous tremolite (nephrite) with an extinction angle $Z \wedge c=20°$ occur at the contact of serpentine and metasedimentary rocks on Mill Creek near Pulga. Thin sections show that the tiny prisms are bent and interlaced, resembling massive talc in the soapstones. The nephrite in this contact zone seems to have crystallized from talc according to the reaction talc + 2 dolomite + 4 silica → tremolite. This reaction was found to be common in the contact zones between the ultramafic bodies and their siliceous wallrocks, as described in the section "Ultramafic Rocks."

METAGABBRO AND HORNBLENDITE

Four large (1–2 square miles) and several small bodies of metagabbro are exposed in the southwestern part of the Bucks Lake quadrangle and in the southern part of the Pulga quadrangle (pls. 1, 2). The two largest ones occur next to the younger plutons, the Hartman Bar pluton and the Granite Basin pluton. The third largest body is in the vicinity of Big Bar Mountain and extends westward across the North Fork of the Feather River. The fourth largest body of metagabbro is exposed just north of the Pulga quadrangle in the southernmost part of the Jonesville quadrangle. All occurrences are inhomogeneous, including masses exceptionally rich in amphibole, in places hornblendite, and grading to parts rich in plagioclase. Gradation to metamorphosed hornblende quartz diorite is common. Some of the border zones of ultramafic bodies consist of hornblendite and metagabbro (for instance, loc. 467).

Metagabbro is gray green to dark green or black and medium to medium coarse grained. The major constituents, green to black hornblende and white to light-greenish-beige plagioclase, can be identified in hand specimens. Thin sections show that epidote is the third major constituent and that quartz and chlorite are present in some metagabbro. Ilmenite and sphene partly altered to leucoxene, magnetite, and apatite are the common accessory minerals. Small flakes of muscovite are included in plagioclase. The percentages of the major constituents and the anorthite content of plagioclase vary considerably. The dark coarse-grained part of the metagabbro, such as the outcrops on the northwestern part of the two largest bodies in the Bucks Lake quadrangle and much of the metagabbro west of the Granite Basin pluton, consists of 70–80 percent hornblende and grades in places to hornblendite. In a common variety the percentages of the major constituents are hornblende 50–70, plagioclase 10–30, and epidote minerals 10–35. Hornblende is either bluish green to green or pale green to almost colorless under the microscope; the darker varieties are strongly pleochroic. Some occurs in large anhedral to subhedral crystals that may include round plagioclase grains, and some is in small prisms, many of them incuded in plagioclase. Clinopyroxene, partly altered to bluish-green hornblende, occurs in a few localities (as locs. 666, 1095). The anorthite content of plagioclase is commonly low (An_{10-15}); however, in parts of the coarse-grained gabbro, plagioclase is andesine (An_{35-45}), and near plutons it is bytownite or anorthite. In these rocks epidote is scarce, and hornblende is darker green, indicating that these parts were probably recrystallized at higher temperatures. In contrast, some other parts of these metagabbro bodies contain chlorite, pale-green to colorless amphibole, and abundant epidote minerals.

The distribution and structure of the well-preserved and highly altered parts in the same mass indicate that the high activity of H_2O near and in the shear zones along the contacts and locally elsewhere was responsible for crystallization of abundant low-grade minerals such as chlorite and epidote. On the other hand, the metagabbro around the Granite Basin pluton is coarse-grained hornblende-plagioclase rock that underwent a second episode of recrystallization during the emplacement of the pluton. In this rock blue-green hornblende occurs in large poikiloblastic crystals or in clusters of prisms having parallel orientation. In locality 796, south of Robinson mine, large pale-green amphibole crystals are rimmed by blue-green amphibole. Small prisms of similar blue-green amphibole are included in plagioclase. The indices of refraction of the blue-green amphibole are between 1.651 ± 0.001 and 1.671 ± 0.001, and specific gravity is 3.17–3.20. A chemical analysis of mainly blue-green material separated from this rock (No. 796, table 2) shows a considerably higher aluminum and alkali contents and a little lower iron content than is common in hornblende from unaltered igneous rocks.

Plagioclase is in anhedral grains that show traces of annealing recrystallization. They show shadowy traces of having been clusters of tiny anhedral grains. The borders of the twin lamellae are jagged or wavy, preserving in part the outlines of the former tiny grains (for example, loc. 546). This is a feature resembling that illustrated earlier (Hietanen, 1951, fig. 21) from a metasomatic gabbro in the Pulga quadrangle. Light-green zoisite with $\alpha = 1.699 \pm 0.001$, $\beta = 1.703 \pm 0.001$, $\gamma = 1.714 \pm 0.001$ occurs as an alteration product in plagioclase, fills fractures, and forms segregations.

Metagabbro included in altered tonalite at Hartman Bar on the north side of the Middle Fork of the Feather River (loc. 205) consists of euhedral stubby hornblende crystals (60–65 percent) and interstitial plagioclase. Thin sections show that green hornblende has altered partly to colorless amphibole that includes small grains of epidote. Plagioclase (An_{30}) contains epidote and sericite as alteration products. Chlorite, muscovite, and magnetite are the minor constituents.

Comparison of the chemical composition of metagabbro (No. 796, table 1) with that of metavolcanic rocks shows the closest similarity to be with the meta-andesite. The percentages of magnesium, sodium, and silicon are only a little higher in the metagabbro, and the percentage of iron is lower.

METADIORITE

Metagabbro grades in places to a lighter colored rock that contains more plagioclase and quartz and less hornblende. The composition of this rock is hornblende quartz diorite. It forms a part of the large mass mapped as metagabbro on the east side of the Granite Basin pluton and the border zones of metagabbro west of Hartman Bar and along Coldwater Creek. Small bodies consisting of similar metadiorite occur with metadacite in the southern part of the area.

In several places, metadacite grades into metadiorite, and some of the rock mapped as metadacite is fine- to medium-grained metadiorite. These two rock types seem to be genetically related. Their mineralogy and chemistry are identical, but their textures reflect different rates of cooling. The intrusive relation between the metavolcanic rocks and metamorphosed intrusive rocks (fig. 20) is exposed on the ridge south of Catrell Creek at an elevation of 4,800 feet (east of loc. 850). Here lens-shaped and dikelike bodies of metadiorite and metagabbro cut the metadacite and metamorphosed sodarhyolite.

The metadiorite consists of plagioclase, quartz, light-green hornblende, epidote, sphene, and magnetite. It is thus mineralogically similar to the metadacite in this area. The differences between the two are mainly textural. In the metadiorite, plagioclase and hornblende grains are large enough to be recognized with the unaided eye, and the rock seems equigranular. Horn-

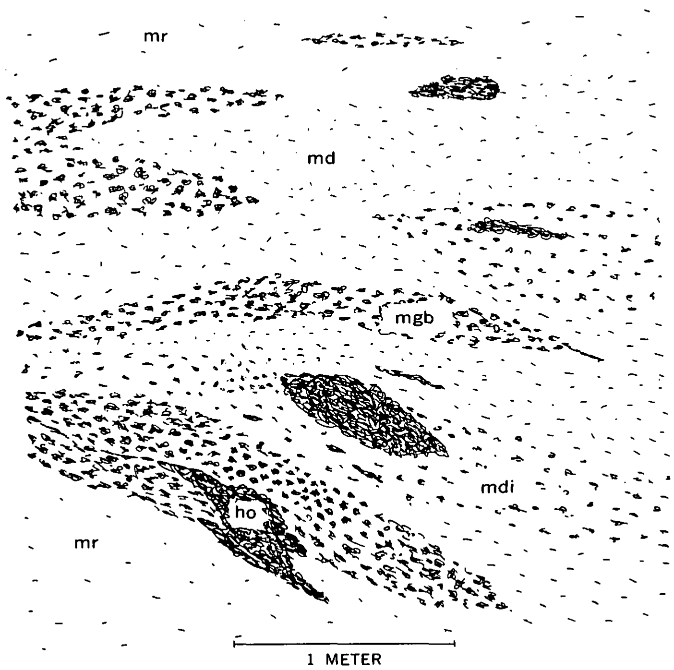

FIGURE 20.—Lenses and dikelike bodies of metadiorite (mdi) and metagabbro (mgb) in metadacite (md) and metasodarhyolite (mr). Dark clots of hornblende (ho) also occur. Ridge south of Catrell Creek; elevation 4,800 feet.

blende is pleochroic in greens (γ=light bluish green, β=light green, α=very light yellowish green, $\gamma \wedge c \sim 20°$). Albitic plagioclase (An_{2-8}) includes abundant fairly large anhedral grains of epidote. Ilmenite, sphene partly altered to leucoxene, and chlorite are visible in some thin sections. Quartz is in small grains or groups of grains that probably represent granulated large grains.

A large sill-like body of metadiorite in the westernmost part of the Pulga quadrangle is mineralogically similar to the metadiorite in the Bucks Lake quadrangle. Variation in grain size and in the ratio of dark and light minerals makes it rather inhomogeneous. Much of this sill is coarse grained, but border zones and many outcrops in the central part are fine to medium grained and resemble metadacite. In some places, hornblende is in long slender prisms that are oriented at random.

The two analyzed specimens of metadiorite (Nos. 465, 532, table 1) are very similar to metadacite. There is only a little more calcium in the metadiorite. This chemical similarity supports the field observation that the two rock types are genetically related.

METATRONDHJEMITE

The northern border zone of a small body of very light gray medium-grained equigranular metatrondhjemite occurs along the south boundary of the Bucks Lake quadrangle. The central part of this body is well exposed south of the quadrangle on the South Branch of the Middle Fork of the Feather River (current study area in fig. 1) where it consists of albite, quartz, biotite, actinolite, and some epidote, muscovite, chlorite and magnetite. Mineral content indicates that it is chemically similar to the metasodarhyolite (table 1, No. 466) and the altered trondhjemite (Hietanen, 1951, table 1, specimen 328).

METAMORPHOSED HYPABYSSAL ROCKS

Metamorphosed hypabyssal rocks are genetically related to metavolcanic rocks and to metamorphosed intrusive rocks. Dikes of andesitic and dacitic composition are mineralogically similar to the meta-andesite and metadacite consisting mainly of albite, epidote, and actinolite. Relict textures of typical hypabyssal rocks are rarely preserved, and only the field occurrence shows that the rock is a dike and not a flow. Metamorphosed dikes of andesitic composition occur at localities 34, 414, and 417, and those of dacitic composition at localities 111, 117, 198, and 673.

Ultramafic dikes consisting mainly of very light green hornblende and interstitial chlorite are exposed along Bear Creek (loc. 108). A small amount of epidote is included in the hornblende. Ilmenite and sphene are partly altered to leucoxene. A greenish-gray dike consisting of a fine-grained feltlike mesh of chlorite and a few small grains of magnetite cuts the soapstone on Soapstone Hill (loc. 762).

Most of the gabbroic dikes consist of altered hornblende-plagioclase rock, and a few contain pyroxene instead of hornblende or in addition to it (loc. 397). Hornblende is commonly in small euhedral prisms, more rarely interstital to plagioclase. The composition of plagioclase ranges from albite to andesine, depending on the degree of alteration of the anorthite component to epidote. Aggregates consisting of chlorite and colorless amphibole and having outlines of olivine occur in the dike that is exposed along the east contact of the small tonalite body on the east slope of Dogwood Creek (loc. 598). Plagioclase (An_{38-40}) in this rock includes small grains of epidote and tiny flakes of muscovite. Magnetite, sphene, and apatite occur as accessory minerals.

In a hornblende gabbro dike about 1 mile south of Grizzly Mountain (loc. 663), euhedral hornblende crystals are included in large plagioclase grains. A dike exposed in the southwestern part of sec. 6, T. 23 N., R. 9 E., (loc. 639) consists of long plagioclase laths oriented at random and of interstitial hornblende in equal amounts. A dike in sec. 4, T. 23 N., R. 8 E., (loc. 730) is a typical example of dark fine-grained lamprophyres that are common in the area. It consists of 70 percent green hornblende, 20 percent plagioclase, and 10 percent epidote.

In an altered diabase dike that is exposed in sec. 21, T. 24 N., R. 8 E., (loc. 95), the major constituents are altered plagioclase and interstitial augite. Epidote, chlorite, and leucoxene occur as alteration products;

most of the small epidote grains are in plagioclase. Chlorite fills shear fractures and envelops many magnetite grains. Sphene is altered to leucoxene.

Gabbroic dikes along Slate Creek (loc. 153) and in the northern part of the Bucks Lake quadrangle (loc. 384) are medium grained and dark greenish gray and consist mainly of altered plagioclase and hornblende. Some interstitial chlorite and quartz and a few grains of magnetite and sphene are the other constituents. Plagioclase has altered to aggregates of epidote minerals and albite that have preserved outlines of the original euhedral crystals. Some of the large hornblende crystals are rimmed by needlelike amphibole and contain remnants of augite. Aggregates consisting of magnetite and chlorite (sp. 153) have outlines suggesting that they were originally olivine. Some of the opaque mineral is ilmenite-magnetite that shows lamellar texture.

Three types of altered dikes of intermediate composition are common: (1) medium-gray fine- to medium-grained dioritic dikes with euhedral hornblende needles oriented at random, (2) dark-greenish-gray dioritic dikes in which augite is partly altered to hornblende and the anorthite component of plagioclase to epidote, and (3) quartz monzonitic dikes.

Examples of the first type are exposed at localities 293 and 412. Hornblende prisms in these dikes are 1–3 mm long; thin sections show that they are the common green variety and make up about 20 percent of the rock. Light-colored minerals are plagioclase and quartz. Epidote occurs as an alteration product in the plagioclase. Magnetite is a common accessory mineral.

Dikes at the mouth of Slate Creek (loc. 694, 711) contain augite phenocrysts that are partly altered to hornblende and rimmed by small radiating needlelike flakes of reddish-brown biotite. Calcic plagioclase has been replaced by a fine-grained mixture of albite and epidote minerals. Quartz occurs as subhedral to anhedral grains and as interstitial granophyre. Magnetite and ilmenite, partly altered to leucoxene, are the accessory minerals.

Quartz monzonitic dikes are medium-gray fine-grained rocks in which needlelike phenocrysts of hornblende, 0.5–1 mm long, are oriented at random. Thin sections show that hornblende is weakly pleochroic (α=pale green, β=green, γ=green) and $Z \wedge c = 21°$. Small subhedral crystals (0.1 mm long) of muscovite, epidote, and chlorite form a considerable portion of the rock. The groundmass is fine grained and consists of quartz and albite. Quartz monzonitic dikes are common in the southern part of the area, where they cut metamorphic rocks (loc. 253) and older plutonic rocks (loc. 208).

The altered plagioclase porphyry that cuts metagabbro at Coldwater Creek (loc. 643) resembles the altered quartz monzonitic dikes, but it is more silicic and has no hornblende. It consists of quartz, albite, muscovite, epidote, chlorite, and some magnetite. Phenocrysts are albite; they are 1–3 mm in diameter and include epidote crystals. Fine-grained porphyritic dikes northwest of Granite Basin (loc. 772) consist mainly of quartz and albite with some biotite and muscovite and very little potassium feldspar.

The most silicic types among the metamorphosed hypabyssal rocks, the quartz porphyries, contain large euhedral to subhedral phenocrysts of quartz. Some of these dikes also contain small phenocrysts of hornblende, and some others, phenocrysts of plagioclase (as at loc. 451). A hornblende-bearing variety cuts serpentine in a roadcut along Bean Creek (loc. 289). Quartz phenocrysts in this rock are about 1 cm in diameter and are granulated. Hornblende phenocrysts are much smaller (0.2–2 mm long), and a few still-smaller euhedral apatite prisms and chlorite flakes (0.1 mm in size) are also embedded in a fine-grained groundmass that consists of quartz, plagioclase, and needlelike amphibole prisms.

The textures of the granulated quartz phenocrysts suggest two phases of growth. The central part is a very fine grained granoblastic aggregate that has outlines of euhedral crystals; it is covered by a shell of somewhat coarser grained quartz. The *c* axis of most grains in the shell radiate out from the central aggregate. The shell includes small euhedral hornblende crystals, some needles of hornblende, and(in a few phenocrysts, epidote. The fine-grained core apparently represents the original phenocryst. The coarser shell formed later, most likely during metamorphism. Hornblende phenocrysts also are zoned; the central part consists of common green hornblende and is rimmed by a thin layer of colorless amphibole, which in turn is covered by a blue-green amphibole similar to that in the groundmass.

A porphyritic dike with quartz and albite phenocrysts cuts phyllite at locality 451. The groundmass of this dike is fine grained and rich in biotite and also contains muscovite, quartz, albite, and some magnetite and hematite.

Dikelike bodies of medium- to coarse-grained silicic rock occur with metadacite and metamorphosed sodarhyolite along Willow Creek (locs. 76, 814), at the mouth of Onion Valley Creek (loc. 343), and south of Granite Basin (loc. 804). These rocks contain euhedral to subhedral phenocrysts of quartz, set in a medium-grained groundmass of quartz, albitic plagioclase, epidote, and either chlorite (locs. 76, 814) or actinolite (loc. 804). Plagioclase includes numerous tiny flakes of muscovite; sphene, partly altered to leucoxene, and magnetite are the common accessory minerals. Mineralogically, these rocks resemble metamorphosed tonalites, but their texture is porphyritic and indicates hypabyssal cooling.

METAMORPHISM

The common mineral assemblages in the metasedimentary and metavolcanic rocks outside the immediate contact aureoles of the Cretaceous plutons are muscovite-biotite-chlorite-albite and epidote-actinolite-albite, indicating metamorphism to the border zone between the greenschist and the epidote-amphibolite facies. Higher grade assemblages occur only in fairly narrow contact aureoles around the plutons. The common indication of the higher grade is coarsening of the grain size toward the pluton over a zone about 1 mile wide. In this zone, assemblages of andalusite-staurolite, andalusite-cordierite, and cordierite-anthophyllite, all with biotite and muscovite, occur in aluminum-rich layers in phyllite. Assemblages of epidote-actinolite-oligoclase (An_{10-12}) and hornblende-oligoclase are common in the metavolcanic rocks; these mineral assemblages are typical of the higher part of the epidote-amphibolite facies. Sillimanite was found only in one locality, in the southern contact aureole of the Bucks Lake pluton, where it occurs with andalusite and cordierite. Pseudomorphs of yellow mica after staurolite occur elsewhere near this southern contact, indicating (together with the assemblage andalusite-sillimanite) that the upper stability limit of staurolite was exceeded here. Plagioclase (An_{40}), green hornblende, quartz, and epidote are common in metabasalt south of the Grizzly pluton and northwest of the Merrimac pluton. This mineral assemblage indicates that there the pressure-temperature conditions of the amphibolite facies were reached in the innermost parts of the contact aureoles.

The upper stability limit of staurolite was also exceeded in the inner contact aureole of the Merrimac pluton east of Chino Creek. There, staurolite occurs with andalusite in the outer contact aureole (loc. 1019) but not in the inner one (loc. 1020), where large porphyroblasts of andalusite crystallized with biotite and muscovite.

Textures in the cordierite- and andalusite-bearing rocks suggest that there have been at least two episodes of metamorphism. In many cordierite and andalusite porphyroblasts, the internal *s* plane, as shown by rows of inclusions, is at an agle to the external foliation that wraps around these early porphyroblasts. In places near the contacts of the plutons, some of the porphyroblasts include the present foliation, indicating postkinematic recrystallization. Staurolite crystallized during and towards the end of the deformation, as shown by a slight bending of external *s* plane around some crystals and by the fact that some of the staurolite includes the external foliation or is included in late crystals of andalusite.

The occurrence of sillimanite with cordierite and andalusite in the quartzite and phyllite just south of the Bucks Lake pluton indicates that during the second episode of recrystallization temperatures in this part of the contact zone were higher than elsewhere. No kyanite crystallized anywhere in the area. The pressure during the recrystallization must have been lower than that at the triple point of the three aluminum silicates. Crystallization of andalusite first with staurolite then with cordierite and sillimanite shows that the metamorphism is of Pyrenean type, as was concluded earlier (Hietanen, 1967). These relations allow an estimation of metamorphic pressures and temperatures. The fact that staurolite occurs with andalusite but was not stable with sillimanite plus cordierite indicates that pressure during the recrystallization was lower than that at the intersection of the andalusite-sillimanite boundary with the upper stability boundary of staurolite. On the basis of the latest experimental work on the stability of staurolite (Hoscheck, 1967, 1968; Ganguly and Newton, 1968; Richardson, 1968) and on the stability of the aluminum silicates (Newton, 1966; Weill, 1966; Althaus, 1967; Richardson and others, 1969), andalusite-sillimanite-cordierite phyllite is estimated to have recrystallized at about 4 kb (kilobars) and at temperatures higher than the upper stability limit of staurolite, thus between 650° and 690°C (fig. 21A). Since muscovite and not potassium feldspar occurs with sillimanite, the upper temperature limit must have been below 650°C (Evans, 1965). In the Pulga quadrangle, where staurolite is included in late andalusite, the early andalusite crystallized first, then staurolite with more andalusite, both being late kinematic. Finally, the latest andalusite crystallized postkinematically. The temperature during this latest phase was higher than during the earlier episode because the upper stability limit of staurolite was exceeded. The lower stability limit of staurolite was determined experimentally by Ganguly and Newton (1968) at about 530°C at 4 kb. The upper limit is 650°C, according to Hoschek (1968). These experimental values are shown graphically in figure 21*A*. In relation to the kyanite-sillimanite transition, this upper stability limit of staurolite seems to be at too high a temperature, because in many regionally metamorphosed areas a kyanite-almandite-muscovite zone succeeds the staurolite-kyanite zone, at pressure not much higher than that of the triple point, thus at about 6-7 kb (Hietanen, 1967, 1968). The total lack of potassium feldspar and absence of any signs of beginning of melting of granitic material in the cordierite-andalusite-sillimanite-two mica phyllite indicate that the peak of the metamorphic temperature in the southern part of the Bucks Lake quadrangle must have been below 640°C (Yoder and Eugster, 1955; Tuttle and Bowen, 1958). These rocks were metamorphosed below the melting temperature of pegmatitic material, thus below 610°C at about 4 kb (Piwinskii, 1968). The shaded area in figure 21*B* shows the stability range of staurolite as deduced from these relations; the heavy line *A–A′* is the possible geothermal gradient during metamorphism in this area.

The metavolcanic rocks were recrystallized under the same physical conditions as the interlayered metasedimentary rocks. Thus, the assemblage epidote-actinolitic hornblende-plagioclase (An_{8-12}) was stable at the peak temperatures 600°–650°C at about 4 kb. Since the early crystallized minerals in the pelitic layers remained stable during the deformation and second episode of recrystallization, the recrystallization in the metavolcanic rocks could have also occurred over a period of time, starting before the latest episode of deformation (which was contemporaneous with the emplacement of the plutons) and reaching its peak after it. The temperature during the postkinematic phase was higher than that during the synkinematic phase. The crystallization of bluish-green rims around colorless and pale-green actinolite prisms reflects these two phases.

Additional information on metamorphism and genetic relationships between the various metamorphic rocks can be deduced from the chemistry of the rocks. Atomic ratios of excess aluminum, calcium, and combined iron, manganese, and magnesium calculated from the chemical analyses of the metavolcanic and metasedimentary rocks (table 1) are shown in an A-C-F diagram (fig. 22). For comparison, the analyses of metavolcanic and metamorphosed igneous rocks of the Merrimac area (table 1, Hietanen, 1951) were plotted in the same diagram. The plots for the metabasalt (Nos. 551, M175), meta-andesite (463, M156), and metadacite (464, M384, M230), as well as those for the corresponding meta-igneous rocks (796, 532, 465), are within the epidote-actinolite-biotite subtriangle, whereas those for the metarhyolite (M406), metamorphosed sodarhyolite (461, M147), and altered tonalite (M328) are within the epidote-almandite-biotite subtriangle. (The epidote-biotite join separates rocks that contain actinolite from those that do not.) The plots for the metadiorite and metagabbro are within the cluster of the plots for the metadacite and meta-andesite; all show a Ca/Fe+Mg ratio of about 42:58. The metamorphosed sodarhyolite and trondhjemite have the same Ca/Fe+Mg ratio, but are richer in aluminum than the meta-andesite and metadacite. In contrast, the Ca/Fe+Mg ratio of metarhyolite (M406) is 14:86, reflecting a low calcium content.

The similarity of the chemistry and mineralogy of the meta-andesite, metadacite, metasodarhyolite, metagabbro, and metadiorite, together with the field evi-

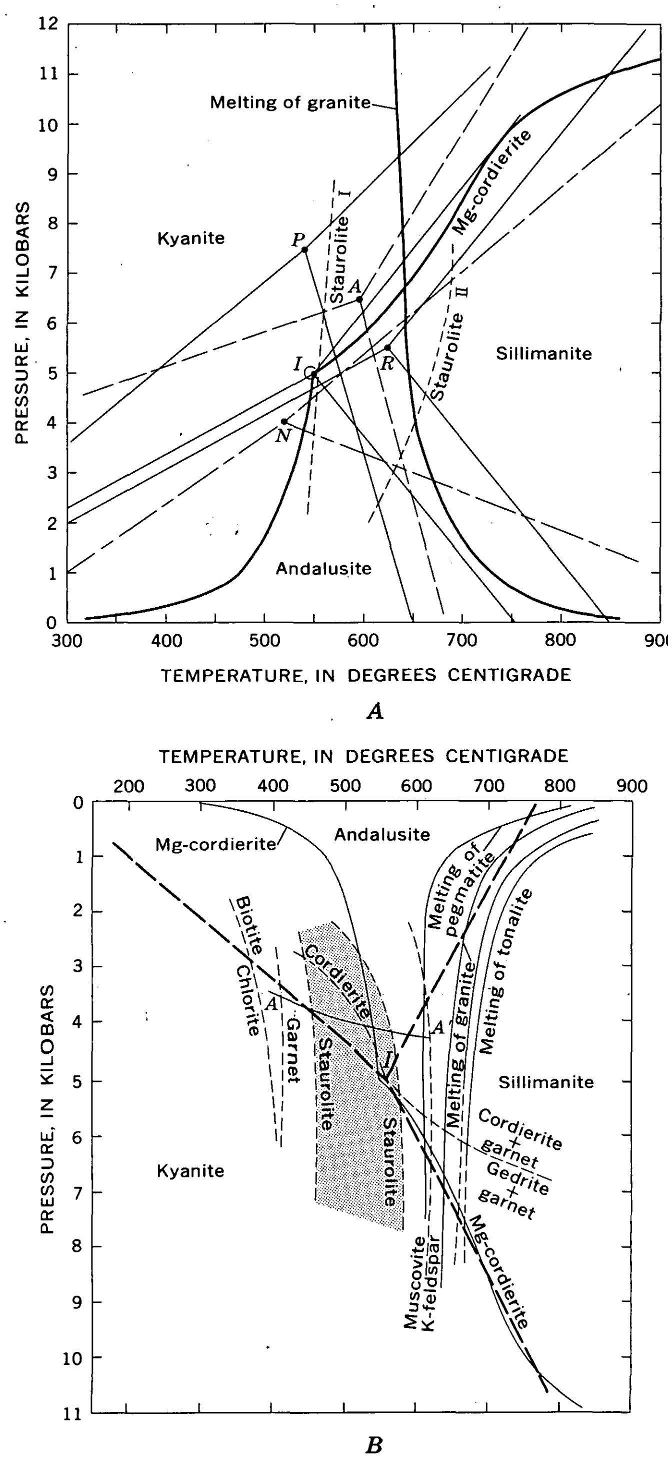

FIGURE 21.—Stability of staurolite during recrystallization. *A*, Stability boundaries of staurolite (Hoschek, 1967, 1968) and Mg-cordierite (Schreyer and Yoder, 1964; Schreyer, 1967) in relation to stability fields of Al-polymorphs according to Althaus (1967, *A*), Newton (1966, *N*), Richardson, Gilbert, and Bell 1969, *R*), and Pugin and Khitarov (1968, *P*). Melting of granite after Luth, Jahns, and Tuttle (1964). *I*, triple point estimated on basis of geologic thermometry and field relations (Hietanen, 1967, 1969). *B*, Field relations and a possible pressure-temperature gradient (*A-A′*) during the recrystallization in the Pulga and Bucks Lake quadrangles. Shaded area shows stability field of staurolite. Melting of igneous rocks after Piwinskii (1968). Modified from Hietanen (1967).

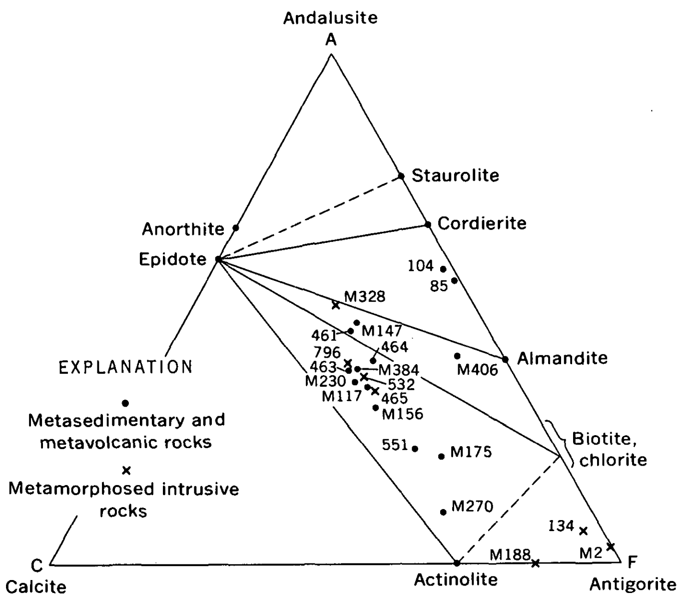

FIGURE 22.—A-C-F diagram for metamorphic rocks. The numbers refer to analyses in table 1; those with prefix M are from Hietanen (1951) with their locations shown on plates 2 and 3. The rock types are as follows: 85, 104 metasedimentary rock, Calaveras Formation; M406 metarhyolite, Horseshoe Bend Formation; 461, M147 metamorphosed sodarhyolite; 464, M384 metadacite; 463, M156 meta-andesite (Nos. 461, 464, 463 from the Franklin Canyon Formation); 551, M175 metabasalt (No. 551 from the Duffey Dome Formation); M230 metatuff; M328 altered tonalite; 465, 532 metadiorite; 796 metagabbro; M117 inclusion of wallrock in quartz diorite; M270 inclusion in monzotonalite; 134, M2, M188 serpentinized peridotite.

dence, suggests a close genetic relationship and a common metamorphism for all these rocks. Metarhyolite contains much less calcium and more potassium than metamorphosed sodarhyolite. Metarhyolite similar to M406 occurs with the metabasalt of the Duffey Dome Formation. Compared with the meta-andesite, this metabasalt (No. 551) has a much lower calcium content and higher sodium content. The differentiation of the Franklin Canyon sequence may have produced a sodarhyolitic end member because of a low potassium content and a high calcium content. This is supported by the fact that each extrusive member of this sequence has a deep-seated and hypabyssal equivalent, all showing closely similar chemical characteristics and probably originating in the same magma chamber. In particular, the composition of metagabbro is close to that of meta-andesite; metadiorite is similar to metadacite; and metamorphosed quartz porphyry and trondhjemite are chemically similar to metamorphosed sodarhyolite. These metamorphosed plutonic rocks occur as small masses and sill-like bodies in the metavolcanic sequence. They were deformed and metamorphosed with the volcanic rocks and thus must have been emplaced soon after the volcanic activity. They are comparable with intrusive rocks in Mount Rainier National Park (Fiske and others, 1963), where Tertiary volcanic rocks are cut by sills and a pluton of the same composition, representing intrusion of magma into its own volcanic pile. In the Bucks Lake quadrangle the composition of the parent magma was close to that of metadacite. Crystallization and segregation of mafic minerals and calcic plagioclase produced metagabbro and meta-andesite; the rest of the magma was left poor in the constituents of the early crystallized minerals and solidified as sodarhyolite and trondhjemite.

PLUTONIC ROCKS

DISTRIBUTION AND DIVISION

The Bucks batholith, a unit on the geologic map of the Bidwell Bar quadrangle (Turner, 1898) and on the Chico Sheet (Burnett and Jennings, 1962), comprises three plutons, each petrologically distinct and separated from the others by a zone of metamorphic rocks. The Grizzly pluton is the largest, underlying about 86 square miles in the central and northern parts of the Pulga quadrangle. The exposed area of the Bucks Lake pluton is about 78 square miles: 55 square miles in the Bucks Lake quadrangle and 23 square miles in the adjoining part of the Pulga quadrangle. The third pluton, the Oliver Lake pluton, is small and kidney shaped and lies north of the other two. It covers 6 square miles in the northernmost part of the Pulga quadrangle and adjoining part of the Jonesville quadrangle.

Other plutons include the Granite Basin pluton, a small round pluton south of the Bucks Lake pluton which has an area of about 6 square miles. The Merrimac pluton, which was studied earlier (Hietanen, 1951), extends into the southern part of the Pulga quadrangle. The eastern marginal zone of a small pluton exposed around Concow Reservoir in the Paradise quadrangle extends to the southwest corner of the Pulga quadrangle. The five western plutons, Grizzly, Oliver Lake, Granite Basin, Merrimac, and Concow, are petrologically similar, grading from hornblende-quartz diorite at the borders to monzotonalite in the central parts. The eastern plutons differ from these and from each other considerably. The Bucks Lake pluton has a pyroxene-bearing center that grades through hornblende diorite to hornblende-biotite-quartz diorite at the borders. In the southern part of the Bucks Lake quadrangle, part of a large pluton, here called the Hartman Bar pluton, and several small stocklike masses consist of biotite and epidote tonalite.

The plutonic rock names used in this report are based on normative amounts of minerals, particularly on the composition of normative feldspar in the rocks, following thus the subdivision of the granitic rocks by Hieta-

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nen (1961). Some of the mineralogically and chemically similar rocks in this area and in the central Sierra Nevada have been given different names (Bateman and others, 1963, 1966, 1967) because those authors used the modal classification.

BUCKS LAKE PLUTON

The Bucks Lake pluton has an exceptional structure and unusual distribution of rock types, indicating a complicated history of intrusion. Its central part consists of massive fine-grained pyroxene diorite and coarser, slightly foliated hornblende-pyroxene diorite; the border zones are strongly foliated hornblende-biotite quartz diorite. A narrow contact zone of hornblende diorite between the pyroxene-bearing center and quartz-rich border zone is texturally similar to the pyroxene-bearing phase and is probably an altered border phase of hornblende-pyroxene diorite. It will be shown that the pyroxene-bearing center is older than the rest of the pluton and can be considered as a huge inclusion in the hornblende-biotite quartz diorite. The evidence is based on the petrology and structure and is supported by absolute age determinations by Grommé, Merrill, and Verhoogen (1967).

PYROXENE DIORITE AND HORNBLENDE-PYROXENE DIORITE

The pyroxene-bearing center of the Bucks Lake pluton is well exposed around Bald Eagle, on Bucks Mountain, and on Camp Rodgers Saddle. Most outcrops consist of two distinct rock types: a fine-grained granoblastic pyroxene diorite and coarser grained hornblende-pyroxene diorite. The fine-grained variety is locally brecciated and occurs as inclusions in the coarse rock, and thus appears to be older. The structural and petrologic relations suggest that fine-grained variety is an early crystallized phase (roof?) of the same magma from which the hornblende-pyroxene diorite crystallized somewhat later. There are distinct differences and similarities in their mineralogy and structure, described in the next two sections.

STRUCTURAL RELATIONS

Swarms of inclusions of fine-grained pyroxene diorite in coarser hornblende-pyroxene diorite are common around Bald Eagle, at Bucks Mountain, and west of Camp Rodgers Saddle. The inclusions are round or ellipsoidal and range from a few centimeters to 1 m or more in diameter (10–20 cm is most common). The inclusions on the east slope of Bald Eagle are round or slightly angular with round corners (fig. 23). On the west slope, where foliation of the host rock is flat lying, the inclusions are flattened parallel to this plane (fig. 24). Flattened and elongated inclusions of fine-grained pyroxene diorite also occur southeast of Cape

FIGURE 23.—Round inclusions of fine-grained pyroxene diorite in coarser grained pyroxene-hornblende diorite. Bucks Lake pluton, 1 mile southeast of Bald Eagle.

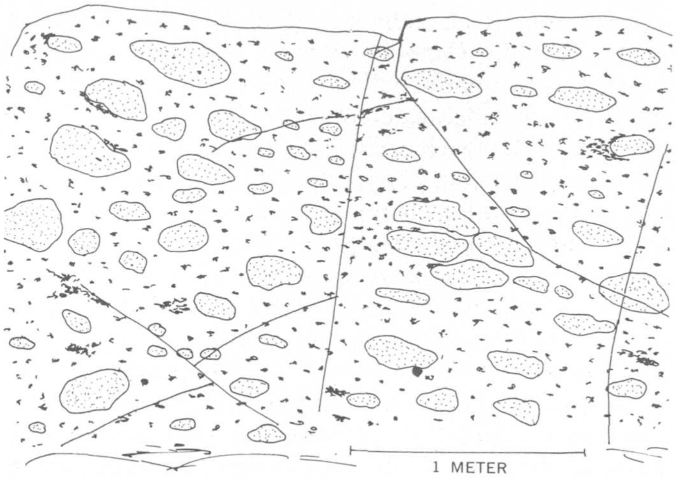

FIGURE 24.—Flattened inclusions of pyroxene diorite in pyroxene-hornblende diorite, north of Bald Eagle (loc. 533).

Lake and 1 mile southwest of Three Lakes near the border zone of the pyroxene-hornblende diorite.

The large inclusions and much of the continuous exposure of fine-grained pyroxene diorite north and south of Bald Eagle contain irregular masses and stringers of coarse-grained hornblende, rarely of hornblende and plagioclase (fig. 25). Similar segregations

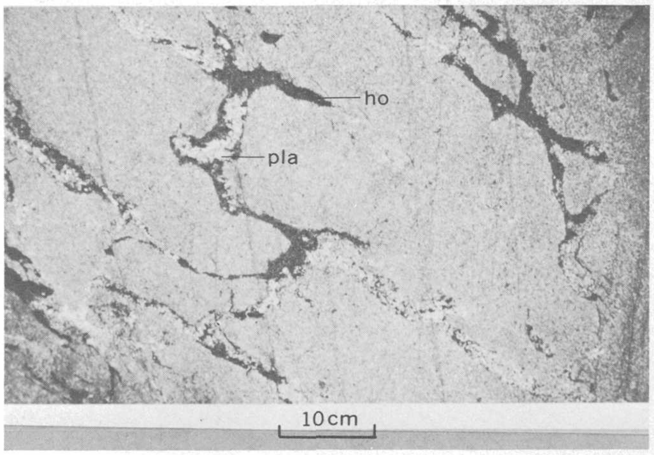

FIGURE 25.—Segregations of hornblende (ho) and plagioclase (pla) in pyroxene diorite, Bucks Lake pluton southeast of Bald Eagle. The faint lines that are nearly perpendicular to the top and bottom of the photograph are joints.

occur in places in coarse-grained hornblende-pyroxene diorite next to and between the fine-grained inclusions. There is every gradation from these hornblende-rich segregations to sporadically occurring clusters of hornblende, which are scattered in the coarse-grained hornblende-pyroxene diorite between the inclusions. Many outcrops give the impression that the fine-grained pyroxene diorite was fractured in an irregular manner and that hornblende crystallized along these fractures and replaced the other minerals, particularly the pyroxene. A part of the components of plagioclase moved out, and another part precipitated as coarse-grained pegmatitic material with hornblende (fig. 25) along the fractures.

At lower elevations around Bald Eagle and Bucks Mountain the hornblende-pyroxene diorite is medium grained and equigranular and shows a weak foliation because of subparallel orientation of plagioclase and pyroxene. Scattered fine-grained inclusions are far less common in this type, and only a few outcrops have segregations of hornblende. In most outcrops the medium-grained variety is fairly homogeneous.

The plane of foliation can be measured in the medium-grained hornblende-pyroxene diorite, but not in the fine-grained pyroxene diorite, except where inclusions are flattened in the plane of foliation. Dips are 15°–40°, and strikes are subparallel to the contacts or to the major regional trend.

PETROGRAPHY

The fine-grained pyroxene diorite and the inclusions consist mainly of plagioclase (An_{48-56}), augite, hypersthene, and magnetite. Sporadic clusters of olive-green hornblende and a few grains of quartz occur in some outcrops. Tiny crystals of apatite are few and scattered. Pyroxene is in small subhedral grains (0.2–0.6 mm, rarely larger) that have rounded corners. Plagioclase crystals are much larger (0.5–2.5 mm) and include small rounded pyroxene crystals (fig. 26). Magnetite

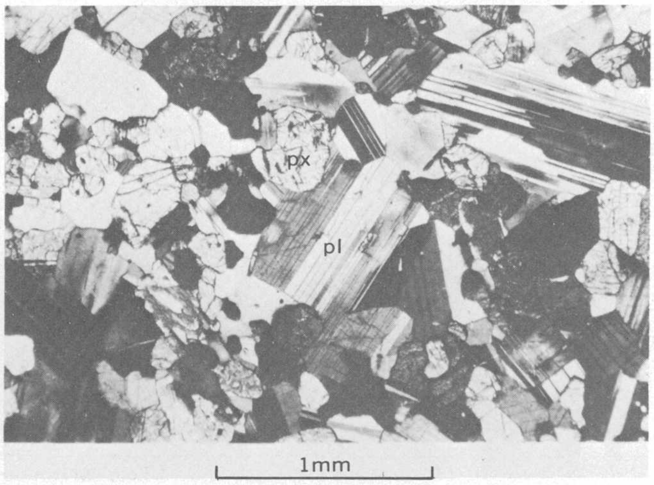

FIGURE 26.—Photomicrograph of pyroxene diorite. Plagioclase (pl) is subhedral, oriented at random, and includes small pyroxene (px) grains. Bucks Lake pluton, location 125, one-half mile northwest of Lower Bucks Lake.

grains, irregular in shape, occur with pyroxene. Plagioclase is complexly twinned but rarely zoned. The zoning when present is very weak and irregular; nevertheless, it indicates a slightly higher An content in the central parts of the grains.

The indices of refraction of hypersthene measured in specimen 125 are $\alpha=1.688\pm0.001$, $\beta=1.699\pm0.001$, $\gamma=1.702\pm0.001$. Diopside in the same rock has $\alpha=1.684\pm0.001$, $\beta=1.691\pm0.001$, $\gamma=1.714\pm0.001$. Some of the hypersthene shows exsolution lamellae of clinopyroxene parallel to the prismatic cleavage. Much of the magnetite is included in pyroxene, and some this included magnetite is enveloped by green hornblende. Chemical analysis of pyroxene diorite (No. 125, table 3) shows about equal amounts of oxides of magnesium, total iron, and calcium and more than 50 percent SiO_2.

In some specimens, pyroxene is partly altered to green hornblende and chlorite. Some of the plagioclase (for instance, in specimen 495) includes fine-grained aggregates of zoisite. In these aggregates, individual grains have subparallel orientation that seems independent of crystallographic planes of plagioclase. These aggregates seem to be remnants of calcium-rich inclusions, perhaps of meta-andesite. Indeed, some of them

TABLE 3.—*Chemical composition, molecular norms and calculated modes of plutonic rocks in the Bucks Lake and Pulga quadrangles*

[Analysts: G. O. Riddle for samples 125, 122, 474, 209, 522, 521; C. L. Parker for samples 707, 844, 837, 699; V. C. Smith for sample 293]

Specimen	125	707	844	293	837	122	474	209	522	521	699
Rock type	Pyroxene diorite	Hornblende diorite	Pyroxene-hornblende diorite	Hornblende diorite dike	Hornblende-biotite quartz diorite			Tonalite	Hornblende quartz diorite	Monzotonalite	
Locality	½ mile northwest of lower Bucks Lake	Workmans Bar, North Fork Feather River	Bald Eagle	South side of Three Lakes	1 mile south of Three Lakes	West shore of Bucks Lake	½ mile south of Silver Lake	1 mile east of Hartman Bar, Middle Fork Feather River	Robinson Mine	0.8 mile south of Grizzly Summit	Big Kimshew Creek east of Bald Mountain
Chemical composition, in weight percent											
SiO_2	52.95	53.14	53.45	56.89	57.76	58.41	62.18	60.83	63.18	66.85	71.61
TiO_2	1.10	1.04	1.05	.76	.82	.81	.66	.44	.61	.40	.22
Al_2O_3	15.75	15.99	17.50	15.98	17.13	16.47	16.28	18.38	17.10	16.58	14.77
Fe_2O_3	2.61	1.96	2.52	1.94	2.19	1.65	1.50	2.73	1.64	1.23	.73
FeO	5.49	5.26	4.59	4.23	3.67	3.60	3.33	2.26	2.70	1.83	.97
MnO	.13	.12	.11	.10	.10	.09	.09	.13	.08	.07	.04
MgO	8.85	8.29	6.92	6.37	4.67	4.93	3.51	2.07	2.56	1.74	.92
CaO	9.03	8.57	8.82	6.83	7.17	7.15	5.69	5.80	5.43	4.16	2.57
Na_2O	3.41	3.45	3.78	3.97	4.05	4.43	4.34	3.53	4.17	4.41	3.94
K_2O	.22	.58	.35	.91	1.14	1.10	1.20	1.39	1.11	1.83	3.50
P_2O_5	.25	.22	.28	.18	.20	.44	.16	.18	.18	.14	.06
CO_2	.01	0	.01	.09	.04	.01	.01	.01	.06	.02	.03
Cl	.01	.06	.02	.01	.04	.04	.02				.01
F	.02	.04	.02	.04	.04	.03	.03	.03	.03	.03	.02
H_2O^+	.19	1.20	.29	1.20	.84	.73	.76	2.04	1.01	.67	.41
H_2O^-	.07	.06	.13	.06	.13	.01	.05	.05	.08	.04	.11
Subtotal	100.09	99.98	99.84	99.56	99.99	99.90	99.81	99.87	99.94	100.00	99.91
Less 0	.01	.03	.01	.02	.03	.02	.01	.01	.01	.01	.01
Total	100.08	99.95	99.83	99.54	99.96	99.88	99.80	99.86	99.93	99.99	99.90
Chemical composition, in ionic percent											
SiO_2	48.58	49.25	49.27	53.01	53.71	54.01	57.96	57.95	59.20	62.31	66.99
TiO_2	.76	.72	.73	.53	.57	.56	.46	.32	.43	.28	.15
$AlO_{3/2}$	17.03	17.47	19.01	17.55	18.77	17.95	17.89	20.64	18.88	18.21	16.28
$Fe^{+3}O_{3/2}$	1.80	1.37	1.75	1.36	1.53	1.15	1.05	1.96	1.16	.86	.51
$Fe^{+2}O$	4.21	4.08	3.54	3.30	2.85	2.78	2.60	1.80	2.12	1.43	.76
MnO	.10	.09	.09	.08	.08	.07	.07	.10	.06	.06	.03
MgO	12.10	11.45	9.51	8.85	6.47	6.79	4.88	2.94	3.58	2.42	1.28
CaO	8.88	8.51	8.71	6.82	7.14	7.08	5.68	5.92	5.45	4.15	2.58
$NaO_{1/2}$	6.07	6.20	6.76	7.17	7.30	7.94	7.84	6.52	7.58	7.97	7.15
$KO_{1/2}$	.26	.69	.41	1.08	1.35	1.30	1.43	1.69	1.33	2.18	4.18
$PO_{5/2}$	.19	.17	.22	.14	.16	.34	.13	.15	.14	.11	.05
CO_2	.01	....	.01	.11	.05	.01	.01	.01	.08	.03	.04
Cl	(.02)	(.09)	(.03)	(.02)	(.06)	(.06)	(.03)	....	....	....	(.02)
F	(.06)	(.12)	(.06)	(.12)	(.12)	(.09)	(.09)	(.09)	(.09)	(.09)	(.06)
OH	(1.16)	(7.42)	(1.78)	(7.46)	(5.21)	(4.50)	(4.73)	(12.96)	(6.31)	(4.17)	(2.56)
Total	99.99	100.00	100.01	100.00	99.98	99.98	100.00	100.00	100.01	100.01	100.00
Total anions	156.56	160.13	158.12	163.06	163.18	162.43	165.94	172.27	168.74	169.42	171.35
Catanorm, in molecular percent											
Q	1.00	1.13	2.06	6.20	7.98	7.08	13.93	18.48	17.64	20.85	26.53
Or	1.29	3.43	2.06	5.41	6.76	6.49	7.13	8.45	6.63	10.88	20.88
Ab	30.25	30.53	33.62	35.78	36.19	39.40	39.06	32.60	37.88	39.85	35.65
An	26.81	26.69	29.69	23.28	25.46	21.93	21.62	28.22	24.95	19.60	12.18
Co	....	....	....	....	....	....	....	1.14	....	.23	.10
Wo	6.36	5.71	4.79	3.55	3.41	4.22	2.23	....	.25	....	....
En	24.21	22.90	19.02	17.69	12.95	13.59	9.75	5.88	7.15	4.83	2.57
Fs	5.31	5.53	4.04	4.32	3.19	3.43	3.36	1.22	2.34	1.54	.76
Mt	2.70	2.05	2.62	2.04	2.30	1.72	1.58	2.94	1.73	1.29	.77
Il	1.52	1.45	1.46	1.07	1.15	1.13	.93	.63	.86	.56	.31
Ap	.52	.46	.58	.38	.42	.92	.34	.39	.38	.29	.13
Cc	.03	....	.03	.23	.10	.03	.03	.03	.15	.05	.08
Hl	.03	.19	.06	.03	.13	.13	.06	....	....	....	.03
Fl	....	.09	....	.11	.10	....	.07	.06	.06	.08	.07
Total	100.02	100.15	100.03	100.09	100.13	100.06	100.08	100.04	100.04	100.05	100.06

TABLE 3.—*Chemical composition, molecular norms and calculated modes of plutonic rocks in the Bucks Lake and Pulga quadrangles*—Continued

Specimen	125	707	844	293	837	122	474	209	522	521	699
Rock type	Pyroxene diorite	Hornblende diorite	Pyroxene-hornblende diorite	Hornblende diorite dike	Hornblende-biotite quartz diorite			Tonalite	Hornblende quartz diorite	Monzotonalite	
Locality	½ mile northwest of lower Bucks Lake	Workmans Bar, North Fork Feather River	Bald Eagle	South side of Three Lakes	1 mile south of Three Lakes	West shore of Bucks Lake	½ mile south of Silver Lake	1 mile east of Hartman Bar, Middle Fork Feather River	Robinson Mine	0.8 mile south of Grizzly Summit	Big Kimshew Creek east of Bald Mountain
Molecular mode											
Quartz	1.00	8.2	1.7	11.2	11.3	11.9	18.4		21.3	23.3	27.7
Orthoclase	1.29	2.0	1.6	...	...	...	...		...	4.9	17.7
Plagioclase	57.06	29.7	58.2	40.5	53.2	51.4	54.5		57.2	57.5	47.1
An	(47)	(34)	(45)	(25)	(40)	(33)	(34)		(37)	(31)	(24)
Hypersthene	23.16	5.0	15.9	...	...	...	...		...	...	...
Diopside	12.73	5.8	4.5	...	...	...	...		...	...	...
Hornblende	...	46.9	16.9	40.3	22	22.6	11.9		6.6	2.7	1.4
Biotite	...	...	...	10.8	19	18.7	19.5		17.8	14.5	7.7
Magnetite	2.70	.4	1.9 (Magnetite and Ilmenite)	...	...	...	.3		.6	.5	.4
Ilmenite	1.52	.5		...	...	...	...		...	...	...
Sphene	...	...	...	...	.4	.1	.4		.3	.2	.1
Apatite	.52	.4	.6	.4	.4	.9	.3		.4	.3	.1
Subtotal	99.98	98.9	101.3	103.2	106.3	105.6	105.3		104.2	103.9	102.2
$AlO_{3/2}$	...	5.0	.1	+2.6	−.3	...	−.4		...	...	...
OH	...	3.6	.4	...	−.8	−.8	−.3		+2.1	...	+.4
CaO	...	...	...	...	...	...	+.2		...	...	...
Total		107.5	101.8	105.8	105.2	104.8	104.4		106.3		102.6

also include green amphibole, and some a few flakes of chlorite and muscovite.

The large sporadic grains of hornblende are irregular in shape and include many rounded grains of plagioclase and some round grains of pyroxene and magnetite forming a poikilitic texture. This hornblende crystallized late and replaced a part of plagioclase, pyroxene, and magnetite.

The coarse-grained pyroxene-hornblende diorite in which the inclusions of fine-grained pyroxene diorite occur consists of plagioclase (An_{46-48}), augite, hypersthene, hornblende, and magnetite. The main differences between the coarse host rock and the fine-grained inclusions are (1) a somewhat lower anorthite content in the plagioclase of the host, (2) a definite increase in the amount of hornblende (40–70 percent of the dark constituents), and (3) a larger grain size of the host. The difference in grain size is due mainly to the larger size of the plagioclase crystals (1–4 mm) and abundant large poikilitic hornblende. In addition to the poikilitic hornblende, green hornblende surrounds many pyroxene and some magnetite grains and is clearly secondary. The plagioclase crystals are tabular with irregular ends and have subparallel orientation.

In chemical composition, the pyroxene-hornblende diorite (No. 844, table 2) is similar to the pyroxene diorite, except for a higher content of Al_2O_3 and a little less FeO and MgO.

The medium-grained homogeneous hornblende-pyroxene diorite has 60–70 percent plagioclase (An_{46-48}), 15 percent hornblende, and 15 percent pyroxenes. Plagioclase crystals are 1–3 mm long and subparallel to the foliation. Most hypersthene crystals are rounded or have rounded ends. Alteration to chlorite and amphibole is common along the cracks, and many grains are spotted green because of partial alteration to hornblende. Pyroxene grains are commonly ½–2 mm long. Magnetite and some apatite occur as accessory minerals. Some hornblende occurs as larger grains similar to the poikilitic hornblende in the coarse variety at Bald Eagle, but most hornblende is in small grains (1–2 mm), many of which have pyroxene cores. The poikilitic grains are usually olive green, whereas the secondary hornblende with pyroxene cores and the hornblende surrounding the magnetite have a bluish tint.

Secondary hornblende becomes more abundant and pyroxene less abundant toward the border zones of the hornblende-pyroxene diorite mass. Remnants of pyroxene in the centers of hornblende crystals can be easily recognized in the field because they are green on a fresh surface and they weather rusty brown.

HORNBLENDE DIORITE

A zone of hornblende diorite—a few meters to several hundred meters wide—occurs between the central pyroxene-bearing diorite and the hornblende-biotite-quartz diorite border zone. At higher elevations the hornblende diorite is medium grained; the dark hornblende crystals contrast with the square crystals of milky white plagioclase. In the canyon of the North Fork of the Feather River, which cuts through 4 miles of this zone, the hornblende diorite is dark gray, partly because of higher amphibole and magnetite contents and partly because of the dark-gray color of fresh plagioclase. The complete gradation from hornblende-pyroxene diorite to hornblende diorite reflects the decreasing amount of pyroxene toward the border zones of the pyroxene-bearing central mass. The intermediate rock next to the hornblende diorite has remnants of pyroxene at the centers of hornblende crystals. Texturally, the hornblende diorite is similar to the pyroxene-bearing diorite, and many features in the mineralogy resemble the central mass more than the quartz dioritic border zone.

Plagioclase (usually An_{37-43}) constitutes about 60 percent of the typical hornblende diorite at higher elevations. Darker masses at Bucks Mountain and in the river canyon have only about 40 percent plagioclase (An_{32-45}) and are thus gabbroic diorite. The grains are tabular, 1–3 mm long, and oriented at random or subparallel to the contact. Segregations of fine-grained zoisite, in places accompanied by some tiny muscovite flakes, form irregular patches in plagioclase clusters. Some large plagioclase crystals (2–5 mm long), many of them zoned, occur in the rock exposed in the river canyon.

Quartz is scarce or absent; when present it is in interstitial small grains. A few sporadic grains of biotite occur in some thin sections.

Hornblende is pale to bluish green; many grains have colorless centers. Some of these centers consist of cummingtonite or of a mixture of cummingtonite and bluish-green hornblende; some include tiny grains of quartz. A few still have remnants of pyroxene surrounded by either colorless or blue-green amphibole. Segregations of dustlike magnetite are common at the outer border of the colorless centers.

At Workman's Bar (loc. 707), several hypersthene crystals enveloped by a thin layer of blue-green amphibole occur in dark gabbroic hornblende diorite that contains abundant colorless amphibole included in green amphibole. Some amphibole grains have outlines of pyroxene and include tiny remnants of pyroxene. Many amphibole crystals with colorless centers occur in nearby outcrops of the same gabbroic hornblende diorite, but pyroxenes are lacking. Clearly, all pyroxene was altered to amphibole in this rock; this is supported by chemical similarities between this rock (No. 707, table 2) and the pyroxene diorite (No. 125).

In gabbroic hornblende diorite near Tobin, remnants of pyroxenes are surrounded by colorless and blue-green amphiboles and pseudomorphs consisting of a fine-grained mixture of amphiboles and chlorite but still showing outlines and relict cleavage of the former pyroxene. In places, this rock is fine grained and has a texture typical of pyroxene diorite. Small grains of ferromagnesian minerals, now pale-green amphibole with bluish rims, have shapes similar to the small grains of pyroxene in the pyroxene diorite. These textures, together with the similarity in chemical composition, show that the hornblende diorite is an altered border zone of the hornblende-pyroxene diorite. In some outcrops (loc. 410), large secondary grains of plagioclase (An_{32-33}), biotite, and hornblende are embedded in the fine-grained partly altered pyroxene diorite, which contains a considerable amount of both pyroxenes, augite, and hypersthene. Similar gabbroic diorite and hornblende gabbro are included in pyroxene diorite near the east border of the Pulga quadrangle south of Bucks Creek.

HORNBLENDE-BIOTITE QUARTZ DIORITE

The outer zone of the Bucks Lake pluton consists of light- to medium-gray coarse- to medium-grained hornblende-biotite quartz diorite. Foliation becomes increasingly more pronounced toward the border of the pluton (figs. 27, 28). For descriptive purposes, this zone is divided into three subzones on the basis of slight differences in mineralogy and texture. The innermost subzone, next to the pyroxene-bearing central mass, has more hornblende and less quartz than the middle subzone, and it contains a few inclusions of pyroxene-

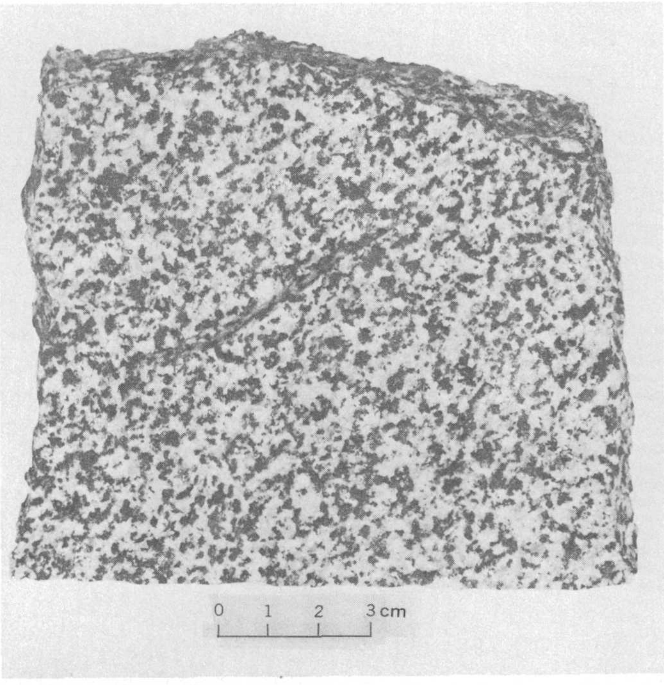

FIGURE 27.—Hornblende-biotite quartz diorite from the Bucks Lake pluton, 1 mile south of Three Lakes (loc. 837). Dark minerals are hornblende and biotite; light-colored minerals and plagioclase and quartz (table 3).

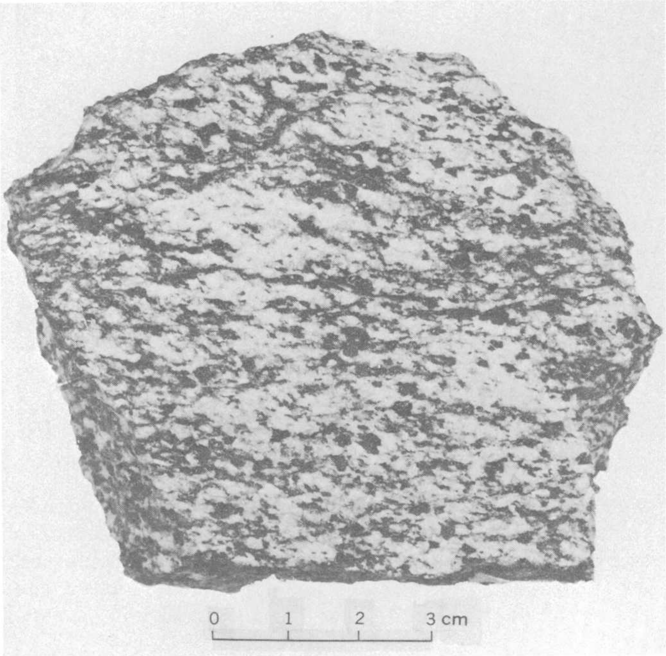

FIGURE 28.—Foliated border zone of hornblende-biotite quartz diorite of the Bucks Lake pluton, 1 mile south-southwest of Spanish Peak (loc. 195). Dark minerals are hornblende and biotite; light-colored minerals are plagioclase and quartz.

bearing diorite. Dark minerals are commonly oriented at random or show only poorly developed parallel orientation. The outermost subzone is strongly foliated and finer grained than the middle zone. It contains abundant long thin sheetlike inclusions of dark fine-grained hornblende-biotite-quartz-plagioclase gneiss, some of it rich in quartz and biotite. Along the southern contact, this zone grades to dark-gray coarse-grained hornblende-rich diorite and hornblende gabbro.

Thin sections show that the innermost subzone consists of 60–65 percent plagioclase (An_{37-40}), 4–5 percent interstitial quartz, about 25 percent hornblende, 5–8 percent biotite and some magnetite, sphene, and apatite. Plagioclase crystals are tabular and 1–4 mm long; where foliation has developed, plagioclase crystals are subparallel to it. Hornblende and biotite crystals are large (1–3 mm) and irregular in shape. Many hornblende crystals have colorless centers that include small rounded blebs of quartz. These centers are similar to those in the outermost zone of the hornblende-pyroxene diorite and the hornblende diorite, and they have the same origin. They originally consisted of pyroxene, and a few of them still include remnants of pyroxene. When the pyroxene was altered to colorless amphibole, the excess SiO_2 was included as small blebs of quartz. Calcium and aluminum needed for this reaction were most likely derived from the anorthite component of plagioclase, as, for example, in the following reaction

$$\underset{\text{3 pyroxene}}{3(Fe,Mg)SiO_3} + \underset{\text{anorthite}}{2CaAl_2Si_2O_8} + \underset{\text{water}}{H_2O} \rightarrow \underset{\text{hornblende}}{Ca_2(Fe,Mg)_3Al_2(OH)_2Si_6Al_2O_{22}} + \underset{\text{quartz.}}{SiO_2}$$

The number of colorless centers decreases away from the pyroxene-bearing rocks. In the dark finer grained inclusions, some pyroxene persists, always covered by a shell of colorless to blue-green hornblende. It seems thus that the hornblende-biotite quartz diorite magma digested some of the earlier crystallized pyroxene-bearing rocks.

Chemical analysis (No. 837, table 3) shows that the innermost subzone contains less MgO and CaO and more SiO_2 and K_2O than pyroxene-hornblende diorite.

The middle subzone is lightest in color. Most of the rock in this zone contains about 15 percent hornblende, 10 percent biotite, 63 percent plagioclase (An_{33-35}), and 7 percent quartz. The hornblende crystals are smaller (1–2 mm long) than in the inner zone and are subparallel to the foliation. The indices of refraction measured in specimen 122 are $\alpha=1.657\pm0.001$, $\beta=1.672\pm0.001$, $\gamma=1.680\pm0.001$. Biotite flakes, 1–2 mm long and having $\gamma=1.650\pm0.001$, are subparallel to the foliation or segregated into laminae. Quartz is in medium-size grains between tabular plagioclase crystals (fig. 29). A few hornblende crystals have colorless centers that include small quartz blebs. Chemical analysis of a specimen (No. 122, table 3) from the west side of Bucks Lake is very similar to that of the inner zone. Pyroxene diorite exposed on a peninsula on the opposite side of

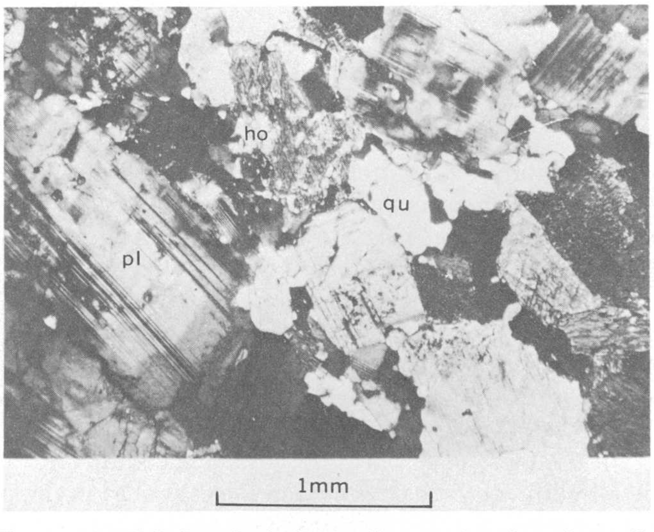

FIGURE 29.—Tabular plagioclase (pl) crystals oriented parallel to the foliation in hornblende-biotite quartz diorite of the Bucks Lake pluton. Quartz (qu) is in interstitial grains of medium size. Hornblende (ho) and biotite are either in individual grains or clustered in irregular lamellae parallel to the foliation. Location 846, 1 mile northeast of Bucks Lake. Crossed nicols.

the lake may extend underwater, parallel to the foliation, and so location 122 may be closer to the contact of this pyroxene diorite than the map shows (pl. 2).

The outermost subzone is strongly foliated and contains sheetlike inclusions of altered wallrocks, now biotite gneiss, biotite-hornblende gneiss, and hornblende gneiss. Thin sections show textures typical of the feldspathized contact aureoles. The large plagioclase grains have round ends and are embedded in a fine-grained matrix of quartz and biotite (fig. 30). Some hornblende

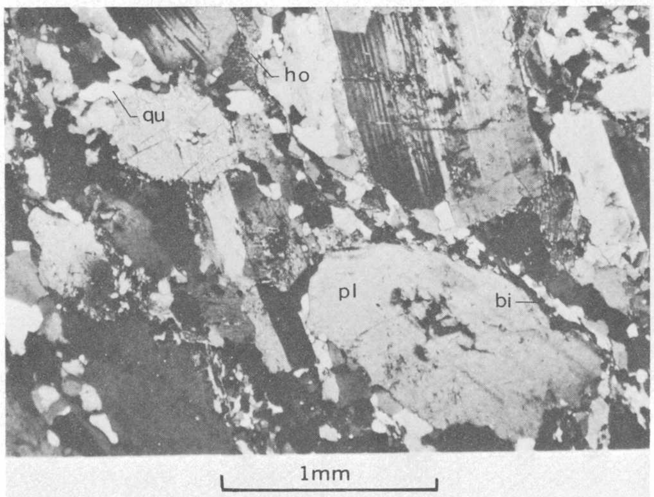

FIGURE 30.—Large plagioclase (pl) grains with round ends enveloped by trains of biotite (bi) and small interstitial grains of quartz (qu). Small hornblende (ho) crystals are clustered with biotite; large ones are rounded and embedded in quartz-biotite matrix. Foliated border zone of the Bucks Lake pluton, location 474, one-half mile south of Silver Lake. Crossed nicols.

is in large crystals that have round ends; smaller grains are clustered with biotite parallel to the foliation. Chemical analysis (No. 474, table 3) shows less MgO and CaO and more SiO_2 than in the inner zones. The indices of refraction of hornblende and biotite in specimen 474 are the same as those in specimen 122. This zone includes a large lens of pyroxene-bearing diorite at Spanish Peak and a small lens at Miller Fork.

Along the southern contact the foliated hornblende-biotite-quartz diorite grades to dark hornblende-rich diorite and hornblende gabbro. Along the northern and northeastern contacts, where the wallrocks are biotite phyllite and biotite quartzite, the contact is gradational over a few meters. Toward the contact the grain size of the phyllite and quartzite increases, and secondary large rounded or tabular grains of plagioclase and anhedral elongate grains of hornblende occur in increasing numbers in these metasediments, which are thus changed to gneissic rocks (fig. 31). The contact between the newly formed, rather fine-grained biotite-hornblende gneiss and the quartz diorite seems sharp in

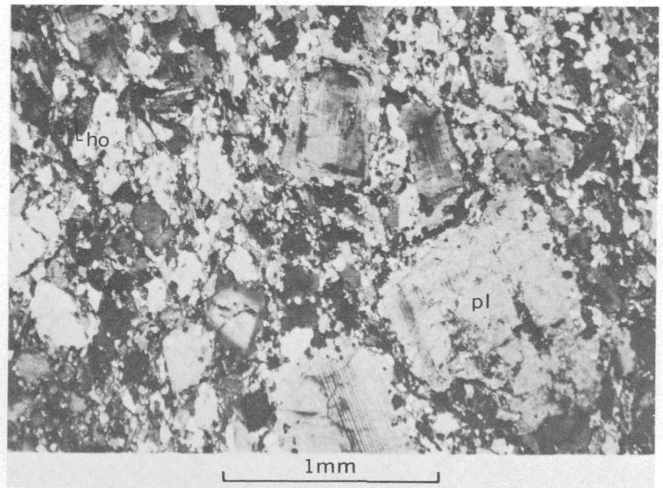

FIGURE 31.—Biotite-hornblende gneiss just north of the northern contact of the Bucks Lake pluton (loc. 721). Large subhedral secondary crystals of plagioclase (pl) and hornblende (ho) are embedded in fine-grained metasedimentary matrix consisting of quartz, biotite, and some hornblende. Crossed nicols.

outcrops, but thin sections show that large plagioclase crystals in the foliated quartz diorite near the contact are enveloped by trains of small grains of quartz and biotite. In places, the matrix between the large plagioclase and hornblende crystals is similar to the biotite gneiss; the only difference between the gneiss and the foliated quartz diorite is that large grains of plagioclase and hornblende are more numerous in the quartz diorite.

The ellipsoidal shape of many secondary plagioclase grains in the gneiss contrasts with elongate and tabular shapes in the typically igneous middle subzone. This ellipsoidal shape persists in the foliated hornblende-biotite quartz diorite 1 mile (see fig. 30) from the contact and thus is restricted to the zone where sheetlike inclusions and other wallrock remnants are common. The rounded ends of plagioclase crystals are bordered by small grains of quartz and not by plagioclase; thus rounding is not the result of postconsolidation granulation of plagioclase. Rounding must be due, instead, either to crystallization in the partly solid, still-mobile matrix or to growth in a solid rock, such as inclusions or walls, that was digested. Differences in other textures, particularly for quartz and biotite, should favor one of these two possibilities.

Firstly, quartz was last to crystallize from the magma and has preserved evidence of relations between the movements and final consolidation in the three subzones. In the innermost subzone, quartz is interstitial, only slightly strained, and not granulated. In the middle zone, quartz is in medium-size strained grains between large tabular plagioclase crystals and has been thus slightly granulated. In the outermost zone, it is in small strained grains, suggesting postconsolidation movement. Thus, the degree of granulation increases toward the border. Such a relationship would result if, for instance, the outermost subzone solidified while magma was still moving in the inner zones. Complete lack of granulation in the innermost zone suggests that quartz there crystallized after the movements had ceased. Thus, consolidation proceeded in a normal way, from the borders toward the center.

Secondly, the following evidence suggests that much of the wallrock (biotite phyllite and quartzite) was digested by the invading magma: (1) Sheetlike inclusions of wallrocks, (2) discontinuous laminae of biotite, (3) numerous small remnants of biotite quartzite, and (4) increase in quartz content and decrease in hornblende content toward the outer border zone. Expansion of the intrusive body was thus partly a mechanical process and partly chemical. Chemical expansion occurred mainly near the walls, where feldspathization similar to that along the present contacts must have been in operation over a long period of time. Thus, the entire outermost shell, with its common wallrock remnants and ellipsoidal plagioclase crystals embedded in a fine-grained quartz and biotite matrix, may have been a gradually migrating contact zone. If so, the pronounced foliation next to the contact is in part inherited from the wallrock, and the oval shapes and sutured borders of the plagioclase crystals result from having grown in generally solid rock.

Both of these explanations differ from the assumption by Grommé, Merrill, and Verhoogen (1967), who considered the foliated texture of the outermost shell to be due to postconsolidation pervasive cataclasis. Thin sections show that some of the tabular plagioclase crystals in the middle zone have been bent and a few broken, probably by movement of a crystal mush that still had some interstitial liquid. Signs of strain in the plagioclase of the outermost shell are no more pronounced than in the middle subzone, and as just discussed, the ellipsoidal shape could not have been produced by cataclasis alone since the crystals are embedded in a mixture of small grains of quartz and biotite. The evolution of this pluton is discussed further after description of the neighboring plutons.

HORNBLENDE GABBRO

The hornblende-rich differentiates that occur as long thin masses along the southern contact of the Bucks Lake pluton consist of plagioclase and hornblende in varying amounts. The darkest varieties contain about 20 percent plagioclase and 80 percent hornblende. These grade to normal hornblende gabbro with about equal amounts of hornblende and plagioclase and further to hornblende quartz diorite with about 30–40 percent hornblende, 60 percent plagioclase, and small amounts of quartz and biotite. All these dark border phases contain abundant alteration products, such as epidote and sericite included in plagioclase, and chlorite and rutile in amphibole. Amphibole is most likely primary; it is green to pale green or colorless. Magnetite and sphene occur as accessory minerals.

SATELLITIC BODIES OF PYROXENE DIORITE AND HORNBLENDE DIORITE

Four small bodies of pyroxene-bearing diorite or hornblende diorite are exposed in the northwestern part of the Pulga guadrangle. Three of these are west of the Grizzly pluton, and one is on the west side of the Oliver Lake pluton.

A small elongate body of pyroxene diorite on the west side of the Grizzly pluton is well exposed at Oak Point. It extends northward for about 2 miles and is 50–200 m thick. The main part is fine-grained gray rock consisting of pyroxene and plagioclase (An_{46-48}) with magnetite and very little hornblende. Pyroxene is mostly augite, but some is hypersthene. Hornblende is an alteration product after pyroxene.

An olivine-bearing dark pyroxenite is exposed in a roadcut 1 mile north of Oak Point (loc. 917). This rock is coarse grained and consists mainly of clinopyroxene, orthopyroxene, and olivine. Some brown hornblende with inclusions of brown rutile and few grains of plagioclase (An_{43}) are interstitial. Olivine is included in clinopyroxene. Orthopyroxene has exsolution lamellae of clinopyroxene parallel to the cleavage. Numerous tiny magnetite grains are also included in orthopyroxene. Some tremolite occurs as an alteration product. This pyroxenite grades over to hornblende-pyroxene gabbro and further to hornblende diorite on its west side.

The hornblende diorite west of the pyroxene diorite at Oak Point resembles mineralogically and texturally the altered border zone of the pyroxene diorite in the Bucks Lake pluton. It consists of medium-gray fine- to coarse-grained hornblende-plagioclase rock with very little quartz and biotite. Plagioclase in hand specimen is bluish gray, a color that makes the hornblende diorite appear darker than is common in hornblende quartz diorite. Thin sections show that hornblende has bluish-green border zones and pale-green to colorless centers that include small round grains of quartz. Plagioclase contains An_{45} and is thus similar to the plagioclase common in the altered pyroxene-hornblende diorite. A small body of hornblende diorite on the east slope of Transfer Ridge about 1 mile west of Oak Point consists of medium-gray hornblende diorite similar to that at Oak Point. Another small body of similar hornblende diorite is exposed along Kimshew Creek northwest of Kimshew Point (loc. 1172).

The hornblende diorite west of the Oliver Lake pluton is separated from the hornblende quartz diorite border zone of that pluton by darker dioritic and gabbroic rocks rich in hornblende. Hornblende-rich gabbroic rocks occur also on the west side, where a dike of hornblende quartz diorite, several meters wide, cuts these rocks. The southern part of this hornblende diorite body consists of dark-gray pyroxene-bearing rock that is very similar to the altered hornblende-pyroxene diorite in the Bucks Lake pluton. Thin sections show that many crystals of green hornblende, the major dark constituent in this rock, have colorless centers consisting of pyroxene and (or) of cummingtonite. The pyroxene was first partly altered to green hornblende, the necessary aluminum being derived from the anorthite molecule of the plagioclase. The remaining central part that was sheltered by green hornblende was altered to cummingtonite that shows characteristic polysynthetic twinning. Some augite and orthopyroxene are still included in a few grains.

The petrologic similarity between the rock types in these small satellitic bodies and the pyroxene and hornblende diorite in the Bucks Lake pluton is striking and can only be explained by a common origin.

GRIZZLY PLUTON

The Grizzly pluton is a typical representative of normally zoned plutons, which are common in the Sierra Nevada (Moore, 1963; Bateman and Wahrhaftig, 1966, p. 121). Its border zone consists of gray medium-grained strongly foliated hornblende-biotite quartz diorite devoid of potassium feldspar (fig. 32). Toward the center, the rock becomes gradually lighter in color and the grain size coarser, and the foliation becomes indistinguishable (figs. 33, 34). The specimens collected across the border zone show a gradual increase in the amount of potassium feldspar and quartz and a decrease in the amount of dark constituents toward the center (table 4). In the central part the average potassium feldspar content is 5–15 percent, quartz 25 percent, and dark constituents (hornblende and biotite) 10–20 percent. The zoned plagioclase ranges from An_{25}

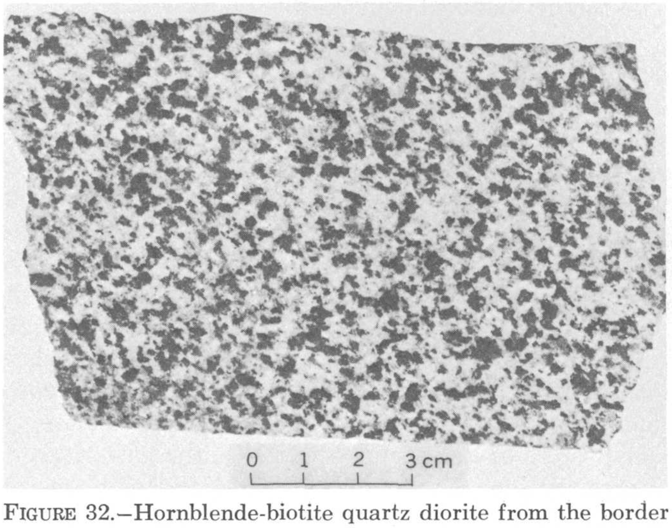

FIGURE 32.—Hornblende-biotite quartz diorite from the border zone of the Grizzly pluton. Dark constituents, hornblende and biotite, are subparallel to the foliation. Light minerals are plagioclase and quartz. Location 886, upper end of penstock at the mouth of Bucks Creek.

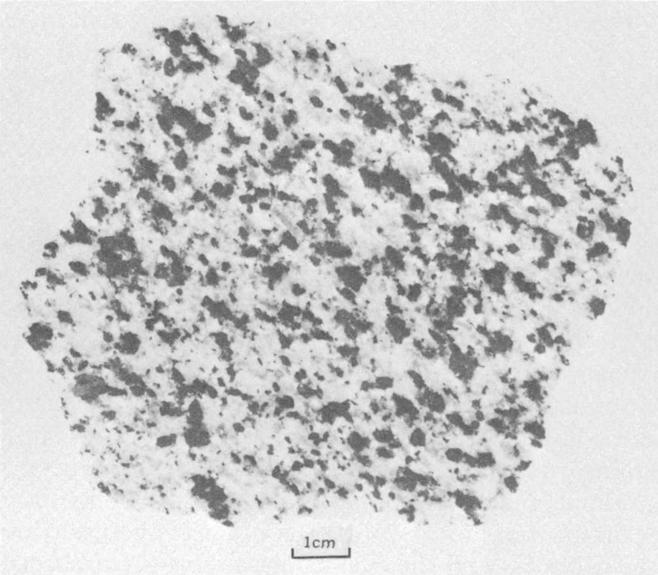

FIGURE 33.—Coarse-grained inner border zone of the Grizzly pluton at Reese Flat (loc. 941). Dark minerals, hornblende and biotite, are subparallel to the foliation, which is still measurable.

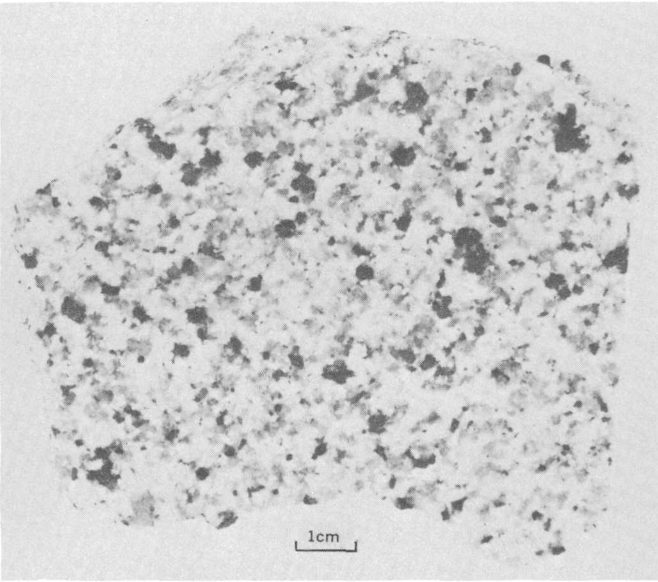

FIGURE 34.—Light-colored monzotonalite from the central part of the Grizzly pluton. Dark minerals are biotite and hornblende, gray is quartz, and white is plagioclase and microcline.

TABLE 4.—*Percentage of the major constituents measured in stained specimens of plutonic rocks*

[Nos. M118, M119, M121 are from Hietanen (1951). Locations 145-699 are from central part of Grizzly pluton]

Rock type	Distance from border in miles	Location	Specific gravity	Plagioclase		Quartz	Potassium feldspar	Hornblende and biotite
			Grizzly pluton					
Hornblende quartz diorite	0.1	894	2.78	An_{37}	50.0	15.0	0	35.0
Do	.1	M118	....	An_{34-44}	48.9	16.7	2.3	32.1
Do	.1	938	2.788		58.0	18.0	0	24.0
Do	.6	887	2.785		54.0	20.0	1.0	25.0
Do	.7	888	2.775	An_{40}	53.8	17.1	4.5	24.6
Do	.8	886	2.80	An_{36}	52.1	14.5	2.9	30.5
Do	1.0	885	2.74		57.0	13.2	.3	29.5
Do	1.2	890	2.783	An_{36}	54.0	20.0	1.0	25.0
Monzotonalite	.3	941	2.736		49.8	22.8	5.2	22.2
Do	.4	1109	2.725		58.5	24.8	5.4	21.3
Do	1.4	893	2.713	An_{31}	54.4	17.4	5.0	23.2
Do	.5	M119	....		45.9	27.7	8.4	18.0
Tonalite		1145	2.731	An_{25-37}	62.3	20.5	1.0	16.2
Do		1146	2.715		57.7	26.9	3.5	13.9
Do		1144	2.72		57.0	23.0	2.0	18.0
Do		1177	2.67		58.4	27.9	2.8	10.9
Monzotonalite		1143	2.70	An_{31-35}	57.4	25.0	6.4	11.2
Do		1178	2.73		50.0	21.6	8.0	20.4
Do		M121	....	An_{25-35}	44.4	30.8	9.6	15.2
Do		915	2.682	An_{33}	52.8	25.4	9.8	12.0
Quartz monzonite		699	2.669	An_{25-35}	48.8	27.3	16.9	7.0
Do		1155	2.726		43.0	28.2	13.9	14.9
Granite northwest border facies		1134	2.642	An_{25-26}	33.3	28.7	31.0	7.0
Granite dike 0.1 mile outside		1135	2.637		32.0	33.7	28.6	5.7
			Oliver Lake pluton					
Hornblende quartz diorite		948	2.795	An_{33-48}	57.9	12.7	0	29.4
Do		1131	2.765		51.4	10.0	2.6	26.8
Do		1127	2.735		55.4	17.3	3.1	24.2
Do		1239	2.74		53.1	24.1	4.5	18.2
Monzotonalite		946	2.72	An_{28-37}	46.0	24.2	12.8	17.0
Do		1132	2.695		47.9	24.2	10.7	17.2
Do		1133	2.70	An_{27}	50.7	18.6	14.5	16.2
			Granite Basin pluton					
Hornblende quartz diorite		522	2.75	An_{25-35}	60.7	18.3	0	21.0
Do		799	2.76		61.6	11.9	0	26.5
Do		747	2.70		58.3	23.5	.7	17.5
Do		798	2.696		57.5	24.9	.8	16.8
Do		775	2.71		55.1	29.4	2.2	13.3
Do		1094	2.673		56.7	23.9	3.0	16.5
Monzotonalite		1255	2.73		54.9	26.2	5.8	13.1
Do		521	2.69	An_{20-47}	59.0	24.0	6.0	11.0
			Merrimac pluton					
Hornblende quartz diorite		1063	2.748		59.1	19.7	0	21.2
Do		1077	2.74		62.1	19.2	.1	18.6
Do		1076	2.67		61.6	25.4	0	13.0
Do		1074	2.86		49.0	8.8	0	42.2
Do		1003	2.73		58.7	21.2	2.6	17.5
Monzotonalite		1002	2.703	An_{25-44}	52.3	27.2	5.5	15.0
Do		M400	....	An_{25-40}	52.6	21.0	5.3	21.0
Do		M312	....	An_{20-30}	58.0	26.0	10.5	10.5
Granitic dike		1009	2.64		47.0	34.3	19.0	5.0
			Concow pluton					
Hornblende quartz diorite		977	2.62	An_{32-35}	56.4	18.7	3.2	21.7
Do		977a	2.61		52.0	34.3	0	13.7
			Hartman Bar pluton					
Trondhjemite		1292	2.70		49.7	43.8	0	6.5
Do		1282	2.673		53.2	39.5	0	7.3
Tonalite		1281	2.75		57.9	31.5	0	10.6
Do		584	2.68	An_{25-40}	61.4	25.9	0	12.7
Hornblende quartz diorite		1214	2.77	An_{38}	61.0	17.7	0	20.4
Aplite dike		585	2.625	An_{25-40}	51.6	25.8	20.9	1.7
			Satellites					
Quartz diorite		1032	2.765	An_{28-38}	59.2	17.9	0	22.8

at the rims to An_{35} at the centers and is thus more sodic than the plagioclase in the quartz dioritic border zone. (See table 4.) The rocks of the central part are granodiorite according to Johannsen's classification (1952).

Subdivision of such rocks by feldspar content has been suggested by Hietanen (1961, 1963). According to this subdivision, the rocks of the interior of the pluton are monzotonalite, and those of the border zone are quartz diorite, with applicable mineral modifiers. The thickness of the quartz dioritic border zone varies: in the southeastern lobe it is more than 1 mile, whereas in the north and west sides of the pluton it is less than a quarter of a mile. Within this range, the percentage of dark constituents decreases from 30–35 percent to about 15 percent. In much of the central part, the monzotonalite is very light colored, containing only 7–12 percent dark constituents, 3–4 percent hornblende, and 3–8 percent biotite.

Thin sections of rock from the strongly foliated border zone show that it consists of hornblende-biotite quartz diorite in which plagioclase (An_{37-38}), hornblende, and biotite are subparallel to the foliation. Plagioclase is in tabular crystals that are 2–3 mm long and have rounded or irregular ends. Hornblende (20–25 percent) and biotite crystals (10 percent) are rather irregular in shape and include quartz, sphene, and magnetite. Remnants of pyroxene occur in the centers of a few hornblende crystals near Storrie, between the west end of Oak Ridge and Grizzly Dome (fig. 35). At Oak Ridge, the pyroxene has $Z \wedge c = 43°$; it is enclosed in a shell of light-bluish-green hornblende which in turn is enclosed in a green hornblende shell. Patchy alteration of pyroxene to light-green hornblende is common. The primary hornblende in the same rock is olive green. Magnetite, sphene, and epidote are clustered with hornblende and biotite. Small euhedral to subhedral crystals of apatite are included in plagioclase.

A few small interstitial potassium feldspar grains appear in the inner part of the foliated border zone. Their size and number increase within 100–400 m from the border toward the center to raise the amount of potassium feldspar along most of the contact from 1 to 4 percent. The rock within this inner border zone is coarser than the rock of the contact zone and slightly less foliated. Its color is lighter, owing to the smaller amount of hornblende (10–20 percent), than in the contact zone. Specimens 885, 886, 887, 888, 890, and 893 (table 4) in the wide border zone of the eastern lobe are representative of this type. Some of the potassium feldspar shows microcline grid structure, and some is untwinned.

A few plagioclase (An_{32-36}) grains have myrmekitic border zones adjacent to the neighboring orthoclase. Grains of epidote are clustered with hornblende. Sphene is principally included in the biotite; some of the opaque iron ore (ilmenite-magnetite?) is rimmed by sphene.

Within the next 200–400 m toward the interior, the potassium feldspar content increases to about 8 percent (Nos. M119, 941, 1109, table 4), and the hornblende content decreases to 10–15 percent. Much of the central part consists of very light gray coarse-grained massive monzotonalite in which potassium feldspar and dark-mineral contents show some local variation. In this rock, plagioclase (An_{25-35}) is in stubby, zoned, and complexly twinned euhedral to subhedral crystals (fig. 36) that are 1–3 mm long. Smaller crystals are included in large quartz grains. Potassium feldspar is interstitial and shows microcline grid structure or is untwinned.

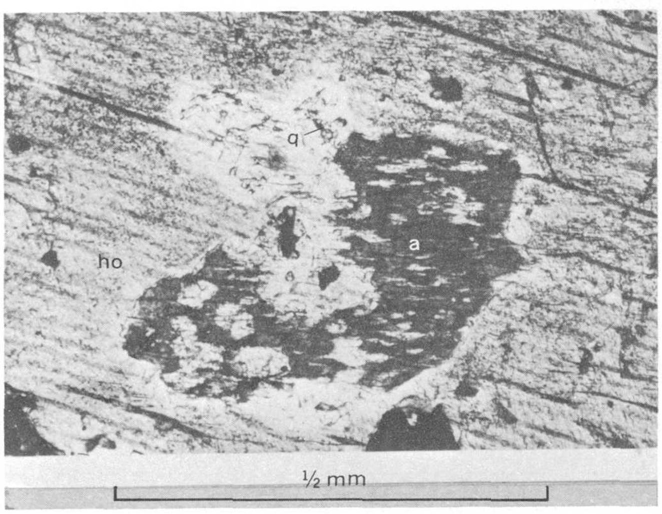

FIGURE 35.—Remnant of augite (a) and tiny inclusions of quartz (q) in hornblende (ho). Hornblende quartz dioritic border zone of the Grizzly pluton (loc. 890). Crossed nicols.

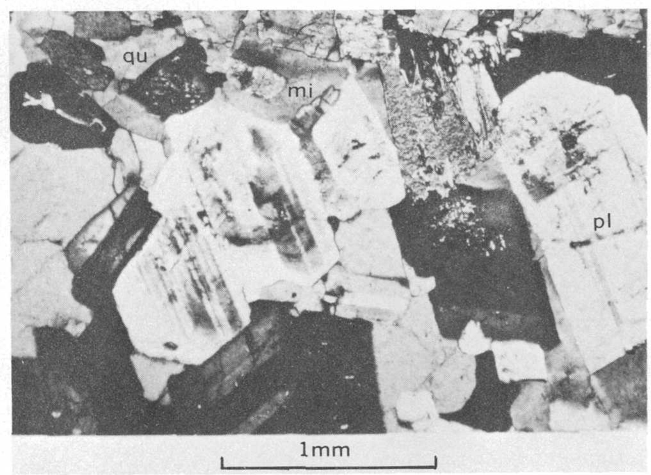

FIGURE 36.—Monzotonalite southeast of Kimshew Point, Grizzly pluton (loc. 915). Microcline (mi) and some quartz (qu) are interstitial. Plagioclase (pl) is in stubby euhedral to subhedral crystals that are zoned and complexly twinned. Crossed nicols.

Biotite is the major dark constituent; flakes are 2–4 mm long, and many are partly altered to chlorite that includes small grains of sphene. Hornblende is in short prisms and in anhedral grains. Small grains of epidote and muscovite are included in plagioclase crystals. Large grains of epidote are clustered with hornblende and biotite. Sphene, magnetite, and apatite are common accessory minerals. Specimens 699, 915, 1143, 1144, 1145, 1146, 1177, and M121 (table 4) are representative of this central part. Chemical analysis of the lightest colored variety (No. 699, table 3) shows lower iron, magnesium, and calcium contents and higher potassium content than the border zone rocks. (Compare Hietanen, 1951, table 1, loc. Nos. 119, 121.)

Granite with about 30 percent potassium feldspar, 33 percent plagioclase (An_{25}), 29 percent quartz, 6 percent biotite, and very little hornblende is the end member of the crystallization differentiation within this pluton (No. 1134, table 4). Dikes of the same composition (No. 1135, table 4) cut the plutonic rocks as well as country rocks. Chemical analysis of such a dike has been given earlier (Hietanen, 1951, loc. 116, table 1).

OLIVER LAKE PLUTON

The Oliver Lake pluton is normally zoned and resembles the Grizzly pluton except for some mineralogic differences in the mafic border zone. The quartz dioritic border zone is more than 1 mile wide on the west side of the southern part of this small pluton; elsewhere it is less than one tenth of this width. The southwestern border zone consists of medium-grained dark-gray slightly foliated rock in which tabular plagioclase crystals are subparallel to the foliation. The plagioclase shows complex twinning and is zoned (from An_{33} at the rims to An_{48} at the centers). The dark constituents, biotite and hornblende, make up 35 percent of the rocks (see table 4) and occur as fairly large crystals. Quartz (about 15 percent) is interstitial. Magnetite, epidote, and sphene are common accessory minerals.

Many hornblende crystals in this dark border zone have light-bluish-green to colorless centers that include tiny round grains of quartz. They are similar to the hornblende in hornblende diorite of the Bucks Lake pluton, in which rock this texture was traced to the alteration of pyroxene to hornblende. A few of the hornblende crystals in the Oliver Lake pluton still include augite, proving that here also the light-colored centers with quartz inclusions are relict texture after digested pyroxene. The northern part of this border zone contains more pyroxene, and near Mud Lake the border zone grades over to pyroxene-hornblende diorite.

Toward the east the dark border facies becomes lighter, and the amount of interstitial potassium feldspar increases. The rock grades over to a monzotonalite with 10–15 percent potassium feldspar (Nos. 946, 1132, 1133, table 4). The rock around Ben Lomond is similar to the light-colored central part of the Grizzly pluton.

GRANITE BASIN PLUTON

The Granite Basin pluton is chemically and mineralogically similar to the Grizzly pluton. Its border zone is hornblende-biotite quartz diorite, and its center is monzotonalite (table 4). On the northwest side, the quartz dioritic border zone is only about 100 m wide; on the east side, it is about 1 mile wide. Most of the border-zone rocks are fairly coarse grained and weakly foliated. A fine- to medium-grained border phase with large plagioclase crystals is exposed on the bottom of Buckhorn Creek. Near the Robinson mine some of the biotite is altered to chlorite, and plagioclase (An_{25-40}) contains epidote and sericite as alteration products. Some large grains of epidote are interstitial, whereas others occur next to biotite and hornblende or, more rarely, are included in these dark minerals. Hornblende is a common green variety and has $\alpha=1.656\pm0.001$, $\gamma=1.678\pm0.001$. Biotite is strongly pleochroic in browns and shows $\beta=\gamma=1.651\pm0.001$. Chemical analyses and calculated norms of this rock (No. 522) are shown in table 3.

The inner border zone of the pluton contains about 3–10 percent interstitial potassium feldspar, most of which shows a good microcline grid structure. Plagioclase is euhedral to subhedral, strongly zoned, and complexly twinned. Many grains show oscillatory zoning. In others, a narrow rim of An_{20-25} surrounds a zoned core of An_{45-47}. In a few cores, a small central part is as calcic as An_{60}. The central parts of many plagioclase crystals contain small grains of epidote and muscovite as alteration products. Large grains of epidote occur with hornblende and biotite. The indices of refraction of hornblende measured in specimen 521 are $\alpha=1.656\pm0.001$, $\gamma=1.679\pm0.001$. Biotite in the same specimen has $\beta=\gamma=1.650\pm0.001$ and thus is virtually the same as that in the quartz dioritic border zone. Quartz is in large- to medium-size grains that include small plagioclase grains or are interstitial. Magnetite, sphene, and apatite are the common accessory minerals.

In chemical composition, this rock (table 3, No. 521) is similar to the monzotonalitic inner border zone of the Grizzly pluton (Hietanen, 1951, table 1, loc. No. 119).

MERRIMAC PLUTON

The Merrimac pluton has already been described in a general way (Hietanen, 1951); some additional information is given here for comparison with the other normally zoned plutons.

The quartz dioritic border zone of this pluton is fairly narrow in the north and northwest, but wide in the northeast, where a coarse-grained massive hornblende quartz diorite rich in hornblende (No. 1074, table 4) is exposed west of the Tertiary basalt that covers a part of the border zone. Dark-gray foliated hornblende quartz diorite is exposed east of the basalt. The quartz dioritic border zone in this vicinity is about 1 mile wide; its mineralogy is similar to that of the border zone of the Grizzly pluton (Nos. 1063, 1074, 1076, 1077, table 4). The inner part of the border zone consists of light-gray massive monzotonalite that contains 2–7 percent potassium feldspar, about 15 percent dark constituents, and 25 percent quartz. In the central part of the pluton, the potassium feldspar content is higher (4–15 percent), and there is less hornblende and biotite (about 5 percent each). The mineralogy and chemical composition are similar to those of a specimen from the Grizzly pluton (No. 699, table 3).

CONCOW PLUTON

The easternmost part of a small pluton around Concow Reservoir is exposed on the southwest border of the Pulga quadrangle. The border zone of this pluton consists of coarse-grained light-gray foliated biotite-hornblende quartz diorite similar to parts of the marginal facies of the Merrimac pluton (table 4). Plagioclase (An_{32-35}) in this rock is subhedral, strongly zoned, and complexly twinned. Biotite in large flakes is the major dark constituent (15 percent). Hornblende (7 percent) is bluish green and occurs in small prisms. Quartz (19 percent) is in large grains that include blocky crystals of plagioclase. Magnetite, sphene, apatite, and epidote occur as accessory minerals.

The contact between this biotite-hornblende quartz diorite and serpentine is exposed along a dirt road north of Pine Cluster Ranch (loc. 976). In the marginal zone of quartz diorite, biotite is altered to chlorite that includes sphene, epidote, and magnetite. Large grains of epidote make up about 10 percent of the rock. Plagioclase (An_{26}) includes grains of epidote and muscovite. A fine-grained gray dioritic dike separates this altered plutonic rock from the marginal talc-carbonate rock of the serpentine mass.

HARTMAN BAR PLUTON AND RELATED BODIES OF EPIDOTE TONALITE

One large and several small bodies of coarse-grained light-pinkish or greenish-gray massive tonalite are exposed in the southern part of the Bucks Lake quadrangle. The northern part of the largest body, the Hartman Bar pluton, is well exposed on the slopes of Hartman Bar ridge and on the steep lower canyon walls of the Middle Fork of the Feather River at Hartman Bar and to the southwest. Biotite is the only dark constituent in this rock. It occurs as large flakes or as rather thick plates (0.5–1 cm long) that are oriented at random and give the rock a distinctive appearance. Thin sections show that the major constituents are plagioclase (An_{25-40}) in large subhedral to anhedral twinned and zoned crystals, strained quartz, biotite, epidote, and some muscovite. Hornblende and potassium feldspar are absent in the border zone exposed in the Bucks Lake quadrangle. In the southern part of the pluton, however, in the area currently being studied (fig. 1), a small amount of hornblende is common. Epidote occurs as large grains next to biotite. Magnetite, apatite, sphene, and zircon occur as accessory minerals.

In the northern border zone exposed along the river, biotite is altered to strongly pleochroic chlorite (γ= green, α=pale-yellow green) that includes sphene, rutile, and leucoxene parallel to the cleavage. Plagioclase is altered to albite that includes numerous tiny grains of epidote and muscovite. The large grains of epidote, many included in chlorite, are more numerous than they are in the unaltered rock. Quartz is granulated and occurs in clusters of small strained grains between the large subhedral crystals of plagioclase. Chemical analyses show that the composition of the border zone (No. 209, table 3) is similar to that of the border zone of the Granite Basin pluton (No. 522, table 3). The unaltered rock farther from the contact has more potassium, all of which is in biotite, and less calcium, and thus much less epidote. These constituents, together with a higher percentage of quartz, bring the composition of the central part to that of tonalite (No. 584, fig. 40). Abundant hornblende in addition to chlorite crystallized near the contact with marble at Marble Cone. This hornblende is bluish green and occurs in slender euhedral to subhedral prisms included in large quartz and albite grains. Albite includes numerous tiny grains of epidote and muscovite. Calculation of chemical composition from the measured mode for sample 584 (quartz 24.7, plagioclase (An_{32}) 60.7, biotite 12.7, muscovite 2.4, epidote 0.5, and magnetite 0.4 percent) shows that the essential difference between the Hartman Bar pluton and the other plutons is not in the chemical composition but in the mineralogy, which indicates lower temperature assemblages and more water for the Hartman Bar pluton.

Several small bodies of epidote-chlorite tonalite similar to the border zone of the Hartman Bar pluton occur in the southeastern part of the Bucks Lake quadrangle. The largest of these extends southward from Lookout Rock; the western part is covered by Eocene pyroclastic andesite. Hornblende quartz diorite borders this tonalite in the southwest. Two other bodies of similar tonalite are at the mouth of Onion

Valley Creek and on the east slope of Dogwood Creek. In all these small bodies, as in the border zone of the Hartman Bar pluton, epidote is one of the major constituents (10–25 percent), and plagioclase, which makes up more than 50 percent of the rock, is albitic. Quartz makes up 20–30 percent, and chlorite 10–15 percent. Sphene and magnetite are the accessory minerals. Small grains of epidote and muscovite are included in plagioclase.

Mineral assemblages in these masses are similar to those in the "altered trondjemite" at Big Bend (Hietanen, 1951, p. 579–580) and may belong to the same age group. Granulation of quartz and crystallization of epidote, muscovite, and chlorite from plagioclase and biotite indicate that these bodies were slightly deformed and partly recrystallized. In the largest body, the Hartman Bar pluton, only the outer zone is strongly altered; the central part remains fairly intact. The intrusive contact relations along the river show that the Hartman Bar pluton is younger than the metagabbro, which is considered to be an intrusive equivalent of meta-andesite.

DIKES ASSOCIATED WITH PLUTONIC ROCKS

Dikes of hornblende gabbro, hornblende quartz diorite, monzotonalite, granite, and pegmatite fill the fracture systems in the plutonic rocks and also cut the metamorphic rocks. These dikes differ from the plutonic rocks only in texture. Some are porphyritic; others are fine grained and similar to those in the Merrimac area (Hietanen, 1951, p. 584–586).

A gabbroic dike along the east contact of a small epidote tonalite mass in the southeast corner of the Bucks Lake quadrangle (loc. 598) consists mainly of hornblende and plagioclase. Hornblende prisms, 1–2 mm long, make up 40 percent of this rock. Aggregates of fine-grained chlorite have outlines indicating that they were formerly olivine crystals. Plagioclase (An_{38-40}) is interstitial to hornblende. Magnetite, sphene, epidote, and apatite are the common accessory minerals. In another gabbroic dike, which cuts the metamorphic rocks about 1 mile south of Deanes Valley (loc. 639), the plagioclase is in slender laths (0.5–1 mm long) oriented at random, and hornblende is interstitial.

A light-gray quartz diorite dike cuts the metamorphic rocks along the road to Bear Ranch Hill (loc. 909). In this dike, clusters and slender prisms of green hornblende are oriented at random in a fine-grained groundmass that consists of oligoclase, quartz, hornblende, and sparse biotite. A fine-grained silica mineral (originally chalcedony) fills the cavities in this dike. Magnetite partly altered to hematite and a few grains of epidote occur as accessory minerals. In the quartz diorite dike at Hartman Bar (loc. 208), phenocrysts are hornblende and plagioclase. Hornblende crystals are euhedral and about 1 mm long; feldspar phenocrysts are studded with alteration products (muscovite and epidote). Groundmass is fine grained and consists of albite, quartz, epidote, and muscovite. Magnetite, sphene, and apatite occur as accessory minerals. A similar dike cuts the metadacite on the Little North Fork of the Middle Fork of the Feather River in the southeast corner of the Pulga quadrangle (loc. 253).

A quartz diorite dike that cuts the hornblende-biotite quartz diorite on the south side of Three Lakes was analyzed chemically (No. 293, table 3). In this dike, large clusters of hornblende and biotite and phenocrysts of hornblende (2–8 mm long) are embedded in a fine-grained groundmass consisting of slender prisms of hornblende (0.5–1 mm long), laths of plagioclase (0.1–0.3 mm long), tiny grains of quartz, small clusters of epidote, and a few grains of magnetite, apatite, and sphene. Clusters of hornblende and biotite have outlines suggesting that they are pseudomorphs after pyroxene.

A fine-grained dark monzotonalite dike in quartzite 1.5 miles north of Deadman Spring (loc. 142) consists of albite, quartz, biotite, and magnetite. Albite in tiny lath-shaped crystals and a few granulated quartz phenocrysts are embedded in a fine-grained groundmass consisting of biotite, albite, and quartz.

Another porphyritic dike of monzotonalitic composition cuts phyllite 1 mile south of Haskins Valley (loc. 451). In this dike, numerous large (0.5–1 cm long) phenocrysts of albite (An_{5-10}) with inclusions of orthoclase and a few phenocrysts of quartz are embedded in a fine-grained groundmass consisting of albite, quartz, and biotite. Magnetite and hematite occur as accessory minerals. Several porphyritic dikes of monzotonalitic composition north of the Bucks Lake pluton are well exposed along the North Fork of the Feather River (locs. 1029, 1039). Large (2–5 mm) phenocrysts of plagioclase (An_{28-43}), in some dikes strongly zoned and containing epidote minerals and muscovite as alteration products, are embedded in porphyritic groundmass consisting of plagioclase, quartz, some orthoclase, hornblende, and biotite partly altered to chlorite. Magnetite, apatite, zircon, and sphene occur as accessory minerals.

A fine- to medium-grained gray granitic dike consisting of about 25 percent potassium feldspar, 35 percent plagioclase, 28 percent quartz, and 12 percent muscovite plus biotite is exposed at the headwaters of Marble Creek (loc. 1086) between metamorphosed sodarhyolite and biotite phyllite. Plagioclase (An_{12}) is in subhedral to anhedral grains that are larger than the other mineral grains and include small round grains of quartz. Granophyric intergrowth of quartz and feldspars is common. Magnetite, hematite, calcite, and epidote occur as accessory minerals.

MAGMA DIFFERENTIATION BASED ON COMPOSITION AND AGE OF PLUTONIC ROCKS

Chemical analyses shown in table 2 were plotted in ionic percentages in several ternary diagrams (figs. 37–40). The analyses published earlier (Hietanen, 1951, table 1) and those of the metamorphosed igneous rocks are included for comparison. The differentiation curves for the plutonic rocks were drawn by visual inspection.

Figure 37 shows variations in normative amounts of quartz, albite, and orthoclase, as computed from ionic percentages. Distribution of the points represents a continuous band that extends from the albite corner to the center of the diagram. The points at the albite corner represent the pyroxene diorite and its alteration product, hornblende diorite, of the Bucks Lake pluton. The points for the inner part of the hornblende-quartz dioritic border zone of this pluton form the next cluster toward the center. In this part, remnants of pyroxene occur in centers of some hornblende crystals. The outer border zone of the Bucks Lake pluton (No. 474), as well as the quartz dioritic border zones of the normally zoned plutons (M118, 522), falls along the curve at 25 percent quartz and 12 percent orthoclase. The composition of the inner parts of the normally zoned plutons plots along the curve that trends toward the ternary eutectic, which is represented by the composition of aplitic granite dike rock (No. M116). This curve represents the trend of differentiation. In the normally zoned plutons, such as the Grizzly pluton, the composition from the border toward the center moves along this curve toward the ternary eutectic, as shown by M118, M119, M121, 699, and M116.

Variation in the normative amounts of plagioclase, quartz, and orthoclase shows a very similar trend (fig. 38). The points are somewhat more scattered, but are nevertheless clustered at the plagioclase corner and near the plagioclase-quartz sideline, from which the composition moves toward the ternary eutectic. In both figures 37 and 38, the points for the metamorphosed igneous rocks are scattered along the sideline away from the orthoclase corner, and many plot into the negative quartz side (below the baseline of the triangle).

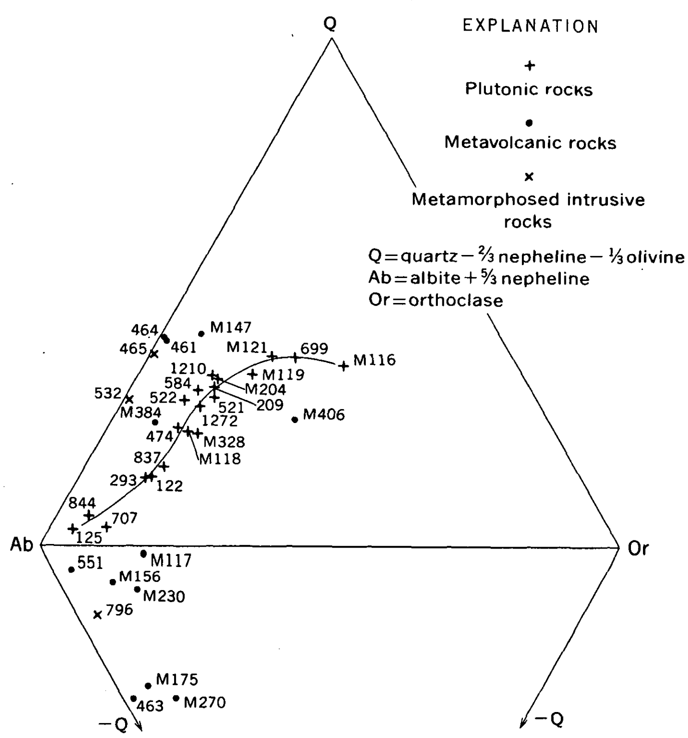

FIGURE 37.—Normative amounts of quartz (Q), albite (Ab), and orthoclase (Or) in molecular percent in the plutonic, metavolcanic, and metamorphosed intrusive rocks in the Bucks Lake and Pulga quadrangles. The numbers refer to the analyses in tables 1 and 3; those with prefix M are from Hietanen (1951). Biotite tonalite (Nos. 584, 1210, 1272) percents are calculated from measured mode.

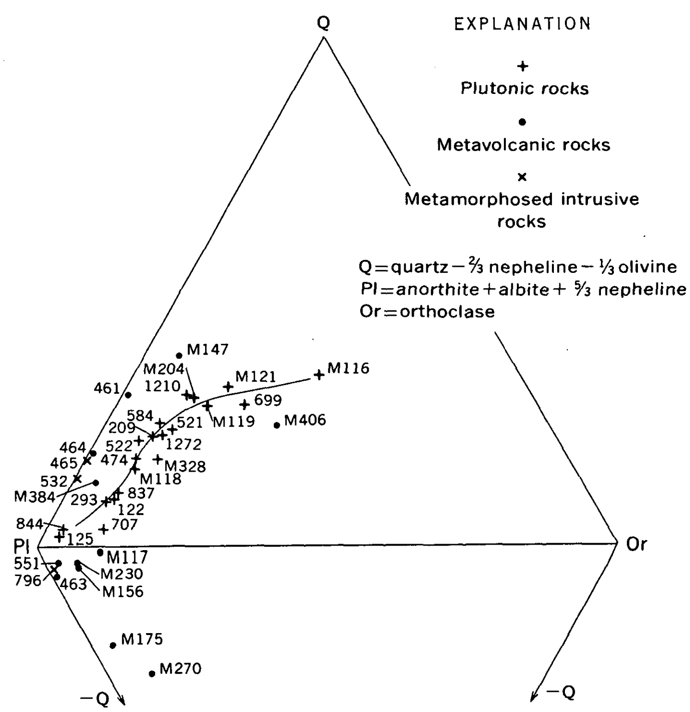

FIGURE 38.—Normative amounts of quartz (Q), plagioclase (Pl), and orthoclase (Or) in the plutonic, metavolcanic, and metamorphosed intrusive rocks in the Bucks Lake and Pulga quadrangles. Numbers refer to analyses in tables 1 and 3; those with prefix M are from Hietanen (1951). Biotite tonalite (Nos. 584, 1210, 1272) percents are calculated from measured mode.

In a Q-M-F diagram (fig. 39), points for the plutonic rocks are clustered along and near a curve close to the F corner. The basic differentiates plot near the M-F sideline, and the silicic end members along the Q-F sideline of the triangle. The points for the metamorphosed igneous rocks show a wider scatter.

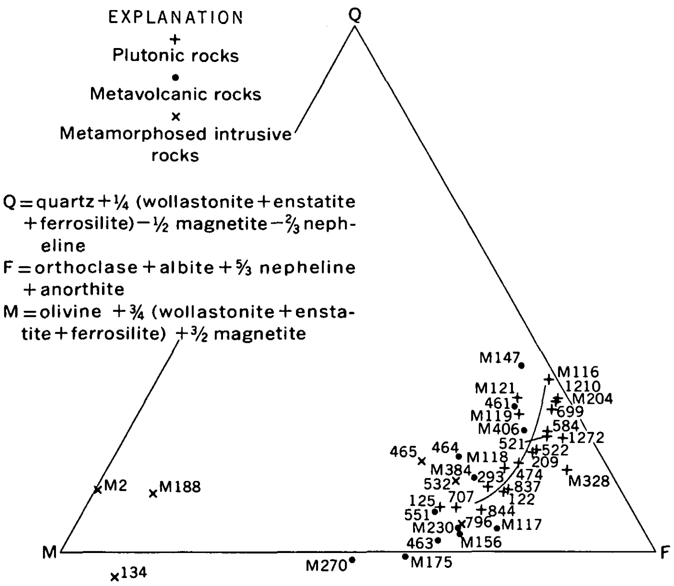

FIGURE 39.—Normative amounts of quartz (Q), mafic constituents (M) as orthosilicates (see Burri, 1964), and feldspars (F) in molecular percent in the plutonic, metavolcanic, and metamorphosed intrusive rocks in the Bucks Lake and Pulga quadrangles. Numbers refer to analyses in tables 1 and 3; those with prefix M are from Hietanen (1951). Biotite tonalite (Nos. 584, 1210, 1272) percents are calculated from measured mode.

Variations in the feldspar composition are shown in the albite-orthoclase-anorthite diagram (fig. 40). Tielines for the subdivision of intermediate and silicic calc-alkalic plutonic rocks on the basis of their normative feldspar content (Hietanen, 1961, 1963) are also shown. The pyroxene diorite and the quartz dioritic border-zone rocks plot near the albite-anorthite sideline between An_{35} and An_{50}, whereas in the inner zone the plagioclase is An_{25-35}, and orthoclase content is 15–30 percent. These rocks have the feldspar content of monzotonalite. Sample 699, which has the highest percentage of potassium feldspar among specimens from the coarse-grained central part of the Grizzly pluton (see table 4), plots close to the tieline through 30 percent orthoclase (thus, at the borderline between the monzotonalite and quartz monzonite). The light-colored border-zone rock on the northwestern part of the Grizzly pluton (Nos. 1134, 1135, table 4) is mineralogically similar to the pegmatite at locality M116 and thus has the composition of a true granite. The differentiation curve in the Ab-An-Or diagram

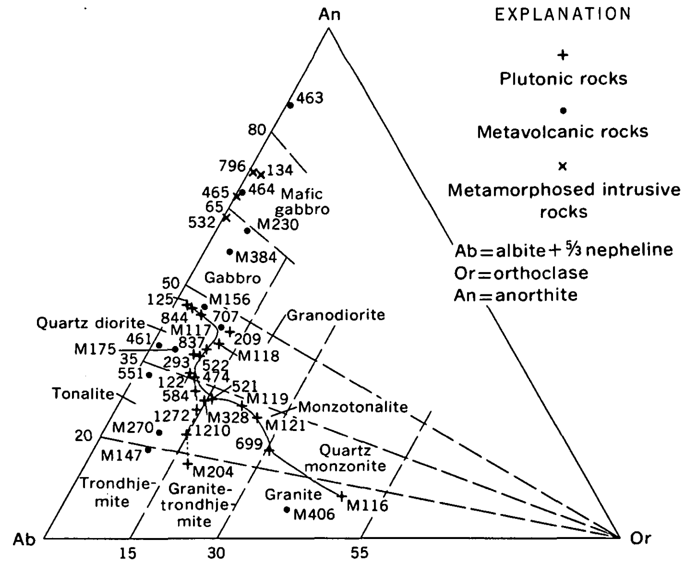

FIGURE 40.—Normative amounts of albite, orthoclase, and anorthite in molecular percent in the plutonic, metavolcanic, and metamorphosed intrusive rocks in the Bucks Lake and Pulga quadrangles. Numbers refer to tables 1 and 3; those with prefix M are from Hietanen (1951). Biotite tonalite (Nos. 584, 1210, 1272) percents are calculated from measured mode.

trends from the diorite side of the albite-anorthite sideline through the monzotonalitic composition to granite. The plagioclase is usually An_{25-37} in the intermediate group with 10–15 percent modal orthoclase (table 4) and thus is less calcic than in the quartz diorite and in its potassium feldspar-bearing equivalent, granodiorite.

The "altered trondhjemite" in the Big Bend area (Hietanen, 1951, table 1, loc. 328) plots in the tonalite group at the tieline through 15 percent orthoclase (M328). The large amount of epidote in this rock as well as in the border zone of the Hartman Bar pluton (No. 209) raises the normative anorthite content much above the modal content. For comparison, granite-trondhjemite (M204) from the Bald Rock pluton south of the Pulga quadrangle (Hietanen, 1951, table 1, loc. 204) and typical samples of biotite tonalite from the Cascade pluton (loc. 1210, 1272, pl. 3) plot outside the trend line in the albite-orthoclase-anorthite diagram. Compton's study (1955) of the modal composition in the southern part of the Bald Rock pluton shows that most of its central part is similar to sample M204, and that this rock grades through monzotonalite and tonalite to hornblende-biotite quartz diorite toward the borders, thus closely following the dotted trend line in figure 40.

Clustering of all points along well-defined curves in all ternary diagrams indicates that all plutonic rocks in the Pulga and Bucks Lake quadrangles are differen-

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tiates of the same parent magma, the oldest offshoots being most basic and the later ones becoming increasingly enriched in silicon, potassium, and iron, as is common in a normal differentiation series. On the other hand, the clustering of points for the hornblende quartz diorite (Nos. 293, 122, 837) halfway between the points for the pyroxene diorite and those for the hornblende-biotite quartz diorite supports the conclusion that the hornblende quartz diorite may have digested large amounts of pyroxene diorite. This conclusion was arrived at on the basis of field evidence and study of thin sections as described in the following paragraphs.

In the field, pyroxene diorite was found as sparse inclusions in the hornblende quartz diorite; more commonly, rusty-weathering pyroxene is seen in the centers of some large hornblende crystals, a texture indicating that the hornblende quartz diorite has digested the older pyroxene diorite. The absence of potassium feldspar in the inner border zone of the Bucks Lake pluton can be a result of digestion of basic pyroxene diorite. Mixing of the pyroxene diorite (No. 125, table 3) and monzotonalite (Nos. M119, M121, table 4) in about equal amounts would give the composition of this zone (Nos. 837, 122). In accordance with this, pyroxene diorite may have occupied much wider areas than are now exposed. The presence of a few inclusions of altered pyroxene diorite in the eastern lobe of the Grizzly pluton suggests that pyroxene diorite was among the older rocks there. The exceptionally wide border zone east of Grizzly Dome consists of hornblende quartz diorite, in which some of the hornblende crystals still have pale-green centers and include small round grains of quartz, a feature that elsewhere was found to be a result of digestion of pyroxene-bearing rocks by the invading younger magma. A similar dark-gray wide border zone is in the southwestern lobe of the Oliver Lake pluton and is there bordered by pyroxene-bearing diorite to the north. In thin sections of rock from this border zone, a few grains of hornblende still include some pyroxene, and others have pale-green centers that include small round grains of quartz. The amount of quartz and biotite is less than in the normal hornblende quartz diorite. Also, this border zone may have digested pyroxene diorite that formerly occupied a much wider area than now exposed.

It is noteworthy that the hornblende in the specimen from the center of the eastern lobe of the Grizzly pluton shows the same age as the hornblende in the altered border zone of the pyroxene diorite (Grommé and others, 1967). The rock type at this locality is quartz diorite, according to Grommé, Merrill, and Verhoogen (1967). The surrounding rocks contain 8–9 percent potassium feldspar (table 4) and are monzotonalitic. It is possible that a part of the hornblende in the specimen collected by Grommé, Merrill, and Verhoogen (1967) is an alteration product after pyroxene and thus of the same age as the hornblende in the hornblende diorite. No age determinations are available for the pyroxene diorite, but the pyroxene is obviously older than its alteration product. According to Grommé, Merrill, and Verhoogen (1967, p. 5676), the hornblende diorite was magnetized at about the same time as the quartz diorite, but pyroxene diorite was magnetized at a different time.

Field evidence and thin sections show that all the pyroxene diorite is older than the hornblende quartz diorite–monzotonalite series. The alteration of pyroxene diorite to hornblende diorite was contemporaneous with intrusion of the hornblende quartz diorite–monzotonalite series. A part of the pyroxene diorite was subsequently digested by this younger magma. According to Grommé, Merrill, and Verhoogen (1967), the younger magma, the Merrimac pluton, is about 130 m.y. (million years) old. Biotite in the outer quartz dioritic border zone of the Bucks Lake pluton is of the same age (129 m.y.) as the monzotonalite (Grommé and others, 1967). The hornblende in the altered parts and in the products of digestion is 142–143 m.y. old and thus is older than the hornblende and biotite in the monzotonalite. Since alteration actually took place during the intrusion of monzotonalite magma, the age 142–143 m.y. is a mixed age. More argon was retained by this secondary hornblende than by the hornblende crystallized from the younger magma. The pyroxene diorite must have been intruded before the pyroxene was altered to hornblende and thus must be older than the mixed age of 143 m.y. The very different magnetic polarity suggests that it could be considerably older. The oldest potassium argon ages determined for hornblende in the plutonic rocks of the Sierra Nevada are 148 m.y. (Evernden and Kistler, 1970). The pyroxene diorite could have a comparable age.

Deformation and alteration of the small tonalite plutons in the southern part of the Bucks Lake quadrangle suggest that these plutons are older than the monzotonalite. The metamorphic rocks provide evidence of two episodes of recrystallization, the later episode being connected with the intrusion of the young plutons. The earlier episode was probably associated with the intrusion of pyroxene diorite and tonalite. It is noteworthy that the highest temperature mineral assemblages in the metamorphic rocks are in the part of the area where several small bodies of epidote tonalite are exposed. The age relations between the tonalite and the pyroxene diorite could not be determined because these rocks are nowhere in contact. The tonalite has a lower temperature mineral assemblage, possibly because the tonalite magma contained more water. No age determinations of the unaltered biotite tonalite of the Hartman Bar pluton are available at present.

TRACE ELEMENTS IN PLUTONIC AND METAMORPHIC ROCKS

A study of trace-element content yields important additional information about the different magma types and supports the conclusion that the metavolcanic rocks and the early intrusive masses are genetically related. Quantitative spectrographic analyses of trace elements in the samples that were analyzed chemically are shown in tables 5 and 6. All samples contain appreciable amounts of Ba, Sr, Cu, V, Cr, Ni, and Zr and low concentrations of Co, Ga, Y, and Sc. A small amount of B (80–90 ppm) occurs in the metasedimentary rocks that contain a few small grains of tourmaline.

For comparison, the average concentrations of trace elements in rocks of very similar silica content in each group (plutonic, metamorphosed plutonic, metavolcanic, and metasedimentary) were plotted in figure 41 as functions of SiO_2, which serves as an index of differ-

TABLE 5.—*Trace elements in plutonic rocks in the Bucks Lake and Pulga quadrangles, in parts per million*

[Analyst: Harriet Nieman. Looked for but not found (some found in samples 293): Ag, As, Au, B, Be, Bi, Cd, La, Mo, Nb, Pb, Pd, Pt, Sb, Sn, Te, U, W, Zn, Ce, Ge, Hf, In, Li, Re, Ta, Th, Ti, Eu]

	125	707	844	293	837	122	474	209	522	521	699
Ag				<2							
B				<50							
Ba	210	250	94	360	420	400	500	550	490	650	520
Be				<10							
Cd				<200							
Co	39	35	16	32	21	22	17	10	13	8	4
Cr	600	610	210	420	174	250	112	17	39	28	17
Cu	200	71	34	71	49	20	28	2	3	10	6
Ga	19	19	8	23	18	18	19	21	19	19	15
Ge				<50							
La				<100							
Mo				<5							
Nb				<20							
Ni	159	490	87	180	62	120	56	<5	26	12	6
Pb				<50							<50
Sc	51	40	11	29	22	30	25	17	17	10	5
Sn				<50							
Sr	560	570	183	810	430	680	400	440	490	440	300
V	320	220	108	180	250	162	137	137	128	76	38
Y	25	35	<20	20	37	26	28	22	22	17	<20
Yb	2	3	<2	3	2	2	2	2	2	1	
Zr	50	90	<50	110	90	210	300	131	110	150	48

TABLE 6.—*Trace elements in metamorphosed igneous and sedimentary rocks in the Bucks Lake quadrangle, in parts per million*

[Analyst: Harriet Nieman. Looked for but not found (some found in samples 85, 465, and 551): Ag, As, Au, B, Be, Bi, Cd, La, Mo, Nb, Pb, Pd, Pt, Sb, Sn, Te, U, W, Zn, Ce, Ge, Hf, In, Li, Re, Ta, Th, Tl, Eu]

	134	796	532	465	551	463	464	461	85	104
Ag				<2	<2				<2	
B				<50	<50				80	
Ba	4	20	20	10	100	5	25	44	1800	800
Be				<10	<10				<10	
Cd				<200	<200				<200	
Co	95	22	24	28	40	32	30	10	7	9
Cr	2200	260	140	290	12	23	204	6	54	87
Cu	110	2	54	110	18	298	172	38	110	70
Ga		13	18	15	20	22	16	15	19	14
Ge				<50	<50				<50	
La				<100	<100				<100	
Mo				<5	<5				<5	
Nb				<20	<20				<20	
Ni	2000	37	36	80	46	45	60	<5	50	36
Pb				<50	<50				<50	
Sc	18	58	53	70	67	91	94	26	19	10
Sn				<50	<50				<50	
Sr		167	270	340	80	450	127	194	60	61
V	50	146	360	200	310	640	280	144	100	72
Y			26	30	60	35	43	23	20	32
Yb			2	4	7	4	5	2	4	3
Zr			<50	70	130		62	112	130	173

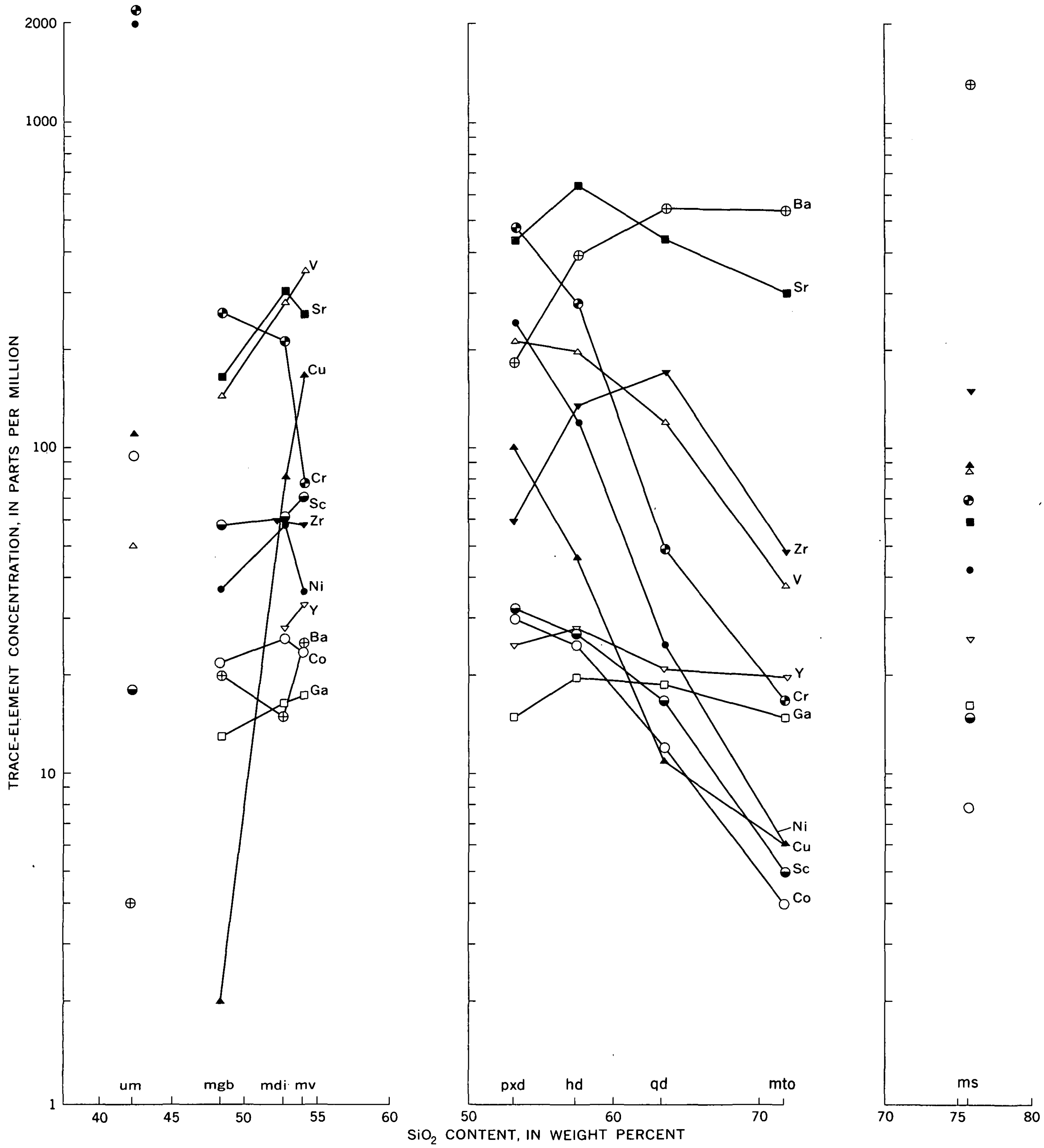

FIGURE 41.—Average trace-element concentration in plutonic, metaigneous, and metasedimentary rocks in the Bucks Lake quadrangle. Pxd, average for pyroxene diorite (Nos. 125, 707, 844, table 5); hd, average for hornblende-quartz diorite (Nos. 293, 837, 122, table 5); qd, average for quartz diorite (Nos. 474, 209, 522; including monzotonalite, 521, table 5); mto, monzotonalite (No. 699, table 5); mv, average for metavolcanic rocks (Nos. 463, 464, 461, table 6); mdi, average for metadiorite (Nos. 532, 465, table 6); mgb, metagabbro (No. 796, table 6); um, ultramafic rock (No. 134, table 6); and ms, average of metasedimentary rocks (Nos. 85, 104, table 6).

entiation. In the plutonic sequence, the decrease of Cr, Ni, Co, Cu, V, and Sc and increase of Ba with increasing SiO_2 are well demonstrated. Sr and Zr show the highest concentration in the intermediate members, whereas the averages of Ga and Y stay nearly constant through the plutonic series. Trace-element content in the border zone of the Bucks Lake pluton is similar to that in the metasedimentary rocks (ms in fig. 41), except for considerably more Sr and less Ba and Cu in the plutonic rock. The high concentrations of Sr reflect the large amount of plagioclase in the quartz diorite, whereas Ba is contained in biotite (0.30 percent), most of which is in the metasedimentary rocks.

Comparison of the plutonic sequence with the metaigneous sequence shows that the average concentrations of Co, Ga, Y, and Zr in the intermediate metaigneous (metadiorite) and metavolcanic rocks (mdi and mv in fig. 41) are close to those in the pyroxene diorite and hornblende quartz diorite (pxd and hd in fig. 41), whereas the average concentrations of Ba and Ni are much lower, those of Sr and Cr are a little lower, and those of Cu, V, and Sc are higher in the metamorphosed igneous rocks.

The ratios K/Sr, K/Ba, Sr/Ba, and Ca/Sr for plutonic and metaigneous rocks were plotted on a logarithmic scale using weight percentage of K as an index of differentiation (figs. 42, 43, 44, 45). In each of four diagrams (figs. 42–45), the metamorphosed plutonic

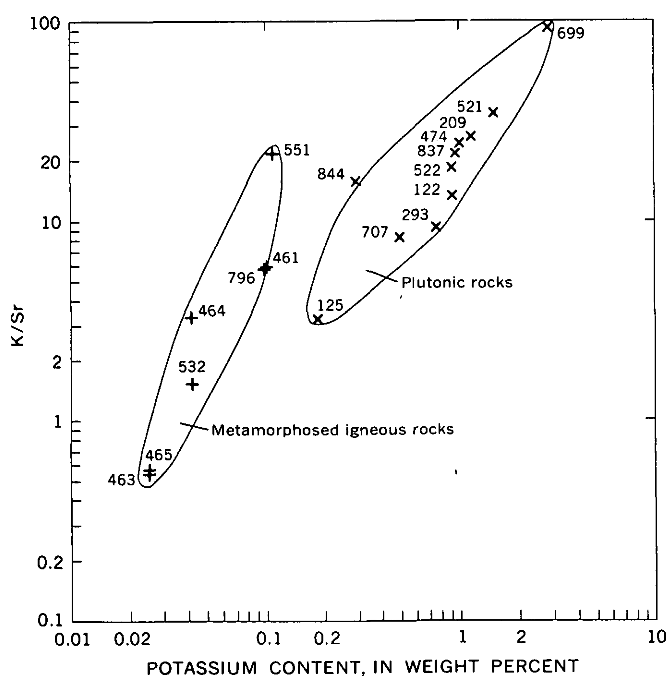

FIGURE 42.—Distribution of potassium-strontium ratios as function of potassium. The numbers refer to tables 5 and 6

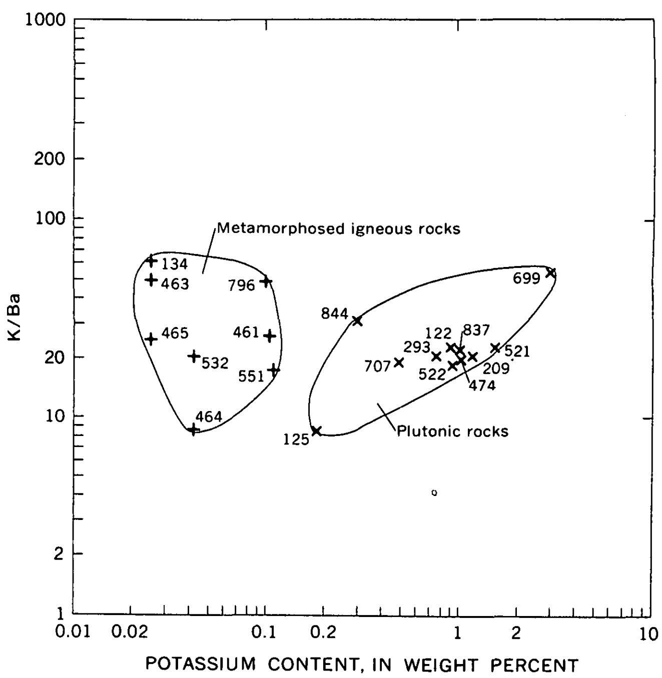

FIGURE 43.—Distribution of potassium-barium ratios as function of potassium. The numbers refer to tables 5 and 6.

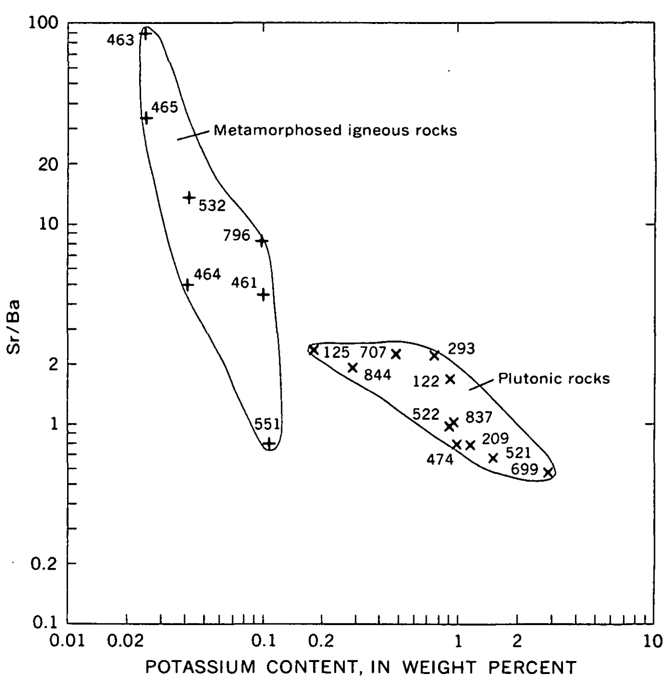

FIGURE 44.—Distribution of strontium-barium ratios as function of potassium. The numbers refer to tables 5 and 6.

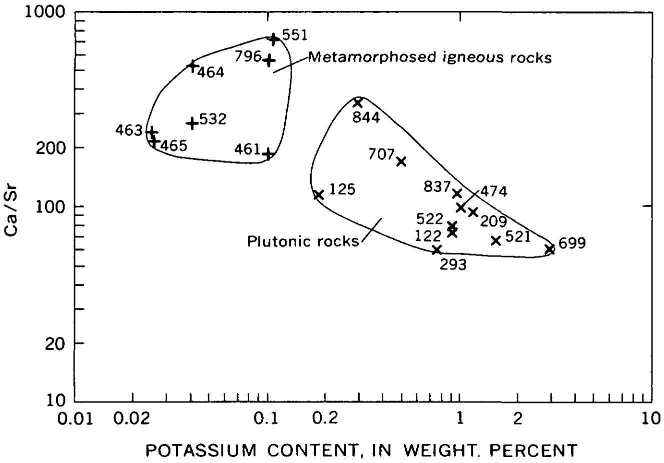

FIGURE 45.—Distribution of calcium-strontium ratios as function of potassium. The numbers refer to tables 5 and 6.

rocks plot within the region defined by metavolcanic rocks; thus the two groups of rocks may be genetically related. In contrast, the younger plutonic rocks are much richer in K, and all ratios show definite trends. K/Sr and K/Ba ratios increase with increasing K, whereas Sr/Ba and Ca/Sr ratios decrease with increasing K.

The trends of K/Ba, Ca/Sr, and Sr/Ba ratios for the plutonic sequence are very similar to those for the continental basalt, as shown by Condie, Barsky, and Mueller (1969), whereas the trend of K/Sr ratio is well between those for submarine and continental basalts of these authors. The metaigneous rocks plot in the area occupied by ultramafic rocks and chondrites. Their exceptionally low K content may have been accentuated during metamorphism by removal of some K. The differences in the trace-element content, together with the low K content, suggest a different source for these two magmatic sequences.

GOLD-QUARTZ VEINS

Several low-grade gold-quartz veins are in the area. Some have been mined in the past; others are now being developed. Averill (1937) described two mines: the Robinson mine on the southeast border of the Bucks Lake quadrangle and the Virgilia at the mouth of Rush Creek on the East Branch of the North Fork of the Feather River. In addition to these two, the Shenandoah mine east of Rich Bar, the Silver Star mine 1 mile east of Coyote Gap, and the Little Nell mine east of Deadman Spring have produced in the past. Mines presently being developed are the Ontop mine on Willow Creek in the Bucks Lake quadrangle and the 3-Ravines mine about 2 miles southwest of Coyote Gap in the Pulga quadrangle. At the Robinson mine on the south border of the Granite Basin pluton, the quartz gold-bearing veins fill fissures mainly in the quartz diorite, but some also occur along the contact between the quartz diorite and the metagabbro. The structures are nearly vertical and strike east-west.

The Silver Star mine is at the northwest contact of the Merrimac pluton. The country rock here is biotite-muscovite phyllite that may have been originally a rhyolitic metatuff. This mine was in operation on a small scale 20 years ago, but has since been abandoned. The gold was washed from claylike material that filled the shear zones and fractures in a quartz vein.

Pabst and Stinson (1960) reported an occurrence of the black uranium-bearing titanium mineral brannerite in the gold-bearing dike at the Little Nell mine at an elevation of 3,300 feet in the southeastern part of sec. 35, T. 23 N., R. 8 E. The dike rock is sericitized, contains albite and quartz phenocrysts, and is cut by veinlets of clear albite and dolomite. Brannerite occurs along the dike wall, in adjoining fractures, and in some albite vugs. Broken crystals of brannerite are coated by gold, which is thus later. Coating of anatase occurs as an alteration product after brannerite.

At the Virgilia mine, low-grade ore occurs in a dioritic dike that is partly silicified. The dike parallels the Melones fault and is only a short distance northeast of this major fracture zone. Averill (1937) reported that parts of this dike are entirely replaced by white quartz and that gold occurs both free and in pyrite. This lode is in the phyllite of the Triassic Cedar Formation and extends parallel to its strike (N. 40° W., dip 70° NE.) about 2 miles to the northwest. It also has been mined about half a mile to the southeast of the river at York Creek. At the north boundary of the Bucks Lake quadrangle, a quartz porphyry dike, part of it strongly sheared, occurs along the strike of this lode.

Another gold-bearing quartz vein is on the southwest side of the serpentine belt, southwest of the Rich Bar fault. Gold has been mined from this vein in the Shenandoah mine at French Creek about half a mile southeast of Rich Bar at the East Branch of the North Fork of the Feather River. At Ontop mine, the gold-bearing quartz vein is along a shear zone that is about 0.1 mile to the northeast of a narrow serpentine belt that probably conceals a fault. The quartz vein follows a sheared and altered quartz porphyry dike that consists of quartz, albite, calcite, muscovite, biotite, and pyrite. This dike continues to the southeast, separating metasodarhyolite in the north from metadacite to the south.

The gold-bearing quartz veins in the 3-Ravines mine are only 30–50 cm thick. Two parallel veins 0.2 miles apart, striking N. 60°E and dipping 60°NW., are being prospected for silver and gold. Gold occurs as flakes, rarely as crystals, between the quartz grains. Most of the ore is low grade, but in places abundant free gold can be seen with the naked eye. Silver-bearing galena also is unevenly distributed through these veins. These lodes are in biotite-muscovite phyllite and can be followed about half a mile along the strike.

AURIFEROUS STREAM DEPOSITS

Small auriferous stream deposits are exposed under the Tertiary volcanic rocks and on the serpentine north of Meadow Valley. These were mapped by Turner (1898), who considered them as Neocene. Similar gravels from the central Sierra Nevada have been dated paleobotanically as middle Eocene by Potbury (1935) and MacGinitie (1941). Plagioclase in the La Porte Tuff of Evernden and James (1964) overlying auriferous gravel has been dated by them as 32.4 m.y. old.

All these gravels have been mined hydraulically for gold, which occurred in the lowest part of a channel where the gravel coarsens. In the Bucks Lake quadrangle two of the mines, the Pine Leaf and the Little California, have been in operation until recently. Most of the auriferous gravels consist of cobbles (5–20 cm in diameter), pebbles (½–5 cm in diameter), and sand. Pebble counts were made of gravel on Bean Creek (sec. 3, T. 24 N., R. 8 E.) at an elevation of 4,600 feet, northwest of the pyroclastic andesite. The results are shown in table 7. Most of the cobbles and pebbles are vein quartz; the second largest group is Silurian clastic quartizite of the Shoo Fly Formation. The nearest outcrop of Shoo Fly sandstone (blastoclastic muscovite quartzite) is more than 1 mile to the northeast; thus material probably was transported from that direction. Only a few small pebbles of other local rocks were found in this gravel.

TABLE 7.—*Pebble count of gold-bearing Eocene gravel on Beans Creek, Bucks Lake quadrangle, sec. 3, T. 24 N., R. 8 E.*

	Size (cm)	Number	Percent
Pebbles			
Vein quartz	½–1	972	64.1
	1–2	228	15.0
Total		1,200	79.1
Chert	½–1	82	5.4
	1–2	41	2.7
Total		123	8.1
Quartzite, Shoo Fly Formation	½–1	115	7.6
	1–2	79	5.2
Total		194	12.8
Grand total		1,517	100
Larger pebbles and cobbles			
Vein quartz	2–5	275	48.7
	5–20	61	10.8
Total		336	59.5
Chert	2–5	0	0
	5–20	0	0
Shoo Fly	2–5	205	36.3
	5–20	24	4.2
Total		229	40.5
Grand total		565	100

TERTIARY VOLCANIC ROCKS

CORRELATION AND AGE

Tertiary volcanic rocks cap wide areas in the southeastern part of the Bucks Lake quadrangle and in the northern part of the Pulga quadrangle. The oldest flows are shown as older basalt of Neocene age on the map of the Bidwell Bar quadrangle (Turner, 1898) and as Eocene basalt on the Chico sheet (Burnett and Jennings, 1962). This basalt underlies pyroclastic andesite of Pliocene age in the area covered by the Chico sheet. Basalt of Pliocene age occurs as small pluglike bodies in the southern part of the Bucks Lake quadrangle, and its silicic differentiate, basaltic andesite, rests on pyroclastic andesite on Mount Ararat. These three units can now be correlated with the Tertiary volcanic rocks that are widespread in the areas to the east and to the south.

The basalt at Walker Plains and some small occurrences of the older basalt in the Bucks Lake quadrangle are shown as a part of the Lovejoy Formation or Lovejoy Basalt by Durrell (1959b). His description of megascopic and microscopic aspects of this basalt in its type section on Red Clover Creek, Blairsden quadrangle (secs. 30, 31, T. 25 N., R. 12 E.) fits well all older basalt in the Bucks Lake and Pulga quadrangles. Durrell (1959b, p. 216) established a late Eocene or possibly earliest Oligocene age for this formation on the basis of stratigraphy in the Blairsden quadrangle, at Table Mountain near Oroville, and in the Sacramento Valley. Dalrymple (1964) determined potassium-argon ages for several specimens of basalt and concluded that the Lovejoy must be more than 13.6 m.y. The overlying rhyolite, however, provided a minimum age of 22.2 m.y. A maximum age of 23.8 m.y. is given by plagioclase in a vitric tuff under the Lovejoy basalt at South Table Mountain near Oroville. Thus, potassium-argon dating yields an early Miocene age for the Lovejoy Basalt.

Pyroclastic andesite overlies Durrell's (1959b) Lovejoy Basalt in the southern part of the Bucks Lake quadrangle and is probably equivalent to the andesite and mudflow breccias of the Pliocene Penman Formation that Durrell (1959b, 1966) described in the Blairsden quadrangle and in the northern Sierra Nevada in general. Much of this unit consists of mudflow breccia and pyroclastic material in which rounded fragments, 1–50 cm long, of light-gray to medium-gray andesite are embedded in fine-grained very light gray debris. Most of the rock east of Bear Creek is medium-gray andesite with sparse black hornblende crystals. This andesite weathers to a gray soil that contains hornblende.

The andesite north of Meadow Valley is darker, and much of it weathers to rusty-brown soil that contains round boulders (20–60 cm in diameter) of andesite.

Basaltic andesite on Mount Ararat and the small pluglike bodies of olivine basalt that are younger than the pyroclastic andesite were mapped by Turner (1898) as "late basalt" of probable Pleistocene age. On the Chico sheet (Burnett and Jennings, 1962), these rocks are shown as Pliocene. Durrell (1959a, 1966) correlated similar basalts in the Blairsden quadrangle with Russell's (1928) Warner Basalt. Comparison of this basalt to Durrell's description leads to the conclusion that all late basalt may be equivalent to the olivine basalt of Pliocene age, as exposed in the Blairsden quadrangle. The small pluglike bodies in the southern part of the Bucks Lake quadrangle have a well-developed columnar structure, usually vertical, but are concentric at locality 317 forming there a structure typical of fumaroles. Pyroclastic material extends eastward from this cone and fills two fractures, several meters wide, in the metamorphic rocks. The basaltic andesite that rests on pyroclastic andesite on Mount Ararat has nearly horizontal, closely spaced joints similar to those in the two-pyroxene andesite on Table Mountain.

PETROGRAPHY

LOVEJOY BASALT

The basalt exposed under the pyroclastic andesite is considered to be a part of the Lovejoy Formation or Lovejoy Basalt of Durrell (1959a, b). The name Lovejoy Basalt is adopted here because in this area and to the south very little, if any, gravel occurs between the lava flows. The basalt is dark gray to black, fine grained, and vesicular. In most localities only one flow is exposed. On many slopes, its flat upper surface forms terraces under younger andesitic material, and its sidewalls are vertical cliffs with irregular columnar jointing. Talus fields at the base of these vertical cliffs contain polygonal to rounded blocks, 10–50 cm in diameter, that in many places cover the lower contact. Vesicles, 1–2 cm in diameter, are common but sparse. Abundant magnetite makes some of the basalt intensely black.

The major constituents of the basalt are plagioclase (An_{50}), augite, magnetite, and olivine. Phenocrysts of plagioclase are few and small (0.3–0.5 mm long), except in the well-crystallized basalt, where plagioclase laths are larger and continue into interstitial areas filled by glass in the finer grained basalt. Olivine is scarce; where present it occurs in euhedral crystals that are about twice the size of augite crystals. The texture of the groundmass is ophitic; tiny laths of plagioclase (0.1–0.2 mm long) are oriented at random or show a slight subparallel orientation. Subhedral augite and magnetite grains (0.04–0.07 mm long) are interstitial. Glass with dendritic magnetite fills the interstices between the other minerals. In a few samples interstitial calcite occurs in small patches. Hematite and goethite fill some of the cavities. Slender colorless needles that transect some of the glass could not be identified for certain. They may be apatite since the chemical analysis shows a high content of P_2O_5. The groundmass in the dark basalt is colored black by fine-grained magnetite. In the gray basalt, magnetite is in cubic crystals, and only a few tiny dust-size particles are included in the interstitial glass, which makes up a small fraction of the rock. Plagioclase constitutes as much as 60 percent of this rock, augite 30 percent, and magnetite 10 percent. Chemical analysis (Hietanen, 1972) shows that the composition is similar to that of andesitic basalts.

PYROCLASTIC ANDESITE

The andesitic rocks in the Bucks Lake quadrangle include light- to medium-gray porphyritic lavas, light-gray pyroclastic material, and mudflow breccia with boulders of andesite. Most of the andesite is studded with light-gray to white equant or elongate euhedral to subhedral phenocrysts of plagioclase (1–4 mm long) and sparsely sprinkled with shiny black slender prisms of hornblende, 1–5 mm long. In some boulders, very dark to black vesicular matrix is studded with small white plagioclase phenocrysts.

Microscopic examination shows that the large blocky phenocrysts of plagioclase (An_{37-50}) are weakly to strongly zoned and complexly twinned. Rims and cleavage planes include small grains of augite and dustlike magnetite. Only the centers of some other crystals contain inclusions. Many plagioclase phenocrysts include irregularly bounded lamellar parts that are isotropic, evidently glass. Augite is the main dark constituent; it is in subhedral to euhedral phenocrysts 1–2 mm long. Most of the andesite contains a small number of hornblende crystals, 1–5 mm long, that are enveloped by a thick layer of fine-grained black magnetite as a result of heating. Extinction angles are small or 10°–15°, suggesting, together with the reddish-brown color, that this mineral is oxyhornblende. In some specimens, hornblende was destroyed completely; the relict black magnetite rims envelop a fine-grained mixture of augite, plagioclase, and dustlike magnetite. In many other specimens, brown hornblende is less oxidized; it is pleochroic in tan and light brown and has an extinction angle of 16°–17°, a little larger than that in the reddish-brown oxyhornblende.

Hypersthene with $-2V{\sim}60°$ is the main dark constituent in a very light gray coarse-grained andesite that occurs as boulders in the pyroclastic material north of Deanes Valley (loc. 136). Hypersthene crystals are subhedral, 0.2–1.5 mm long, and have reddish-brown rims. A weak reddish-brown coloration extends inward toward the center of the crystals, camouflaging the pleochroism. A few crystals of colorless augite occur with hypersthene and include small grains of hypersthene. Magnetite occurs as large subhedral crystals (0.2–0.5 mm long) and as small round to subhedral grains in the groundmass. Groundmass of the porphyritic andesite consists of small blocky crystals of plagioclase, augite, and magnetite. Interstitial glass is common, but rarely plentiful.

"LATE BASALT" OF TURNER (1898)

The olivine basalt and basaltic andesite that are younger than the pyroclastic andesite differ mineralogically mainly in their olivine content. The basalt in the plugs is rich in olivine, whereas the basaltic andesite has very little or no olivine. Some of the andesite is rich in plagioclase and contains orthopyroxene and clinopyroxene. Chemical composition of these rocks was discussed earlier (Hietanen, 1972).

OLIVINE BASALT

The olivine basalt is fine- to medium-grained gray rock that is studded with yellowish-green olivine phenocrysts, 1–4 mm long. Thin sections show that large euhedral to subhedral olivine crystals are embedded in a fine-grained groundmass consisting of tiny laths (0.1 mm long) of plagioclase, crystals of augite, olivine, and magnetite, and interstitial glass. In places (loc. 587), augite also occurs as phenocrysts, but these are smaller (0.2–1 mm long) than the crystals of olivine. The basalt at locality 317 contains more plagioclase and less olivine than most other basalt and is accordingly lighter in color. At locality 510, the grain size of the basalt becomes increasingly coarser toward the center of the circular outcrop. The fine-grained borders of this plug are separated from the surrounding metamorphic rocks by powdery microbreccia. A small plug-like body half a mile to the south (loc. 513) consists of similar olivine-rich basalt. The indices of refraction of olivine in this rock are $\alpha=1.690\pm0.002$, $\beta=1.710\pm0.002$, $\gamma=1.725\pm0.002$ indicating, according to Winchell and Winchel (1951), the composition $Fo_{73}\,Fa_{27}$.

TWO-PYROXENE ANDESITE

The basaltic anesite on Mount Ararat and on a hill west of it is light gray, fine to medium grained, and equigranular. Thin sections show a well-developed flow structure that is due to subparallel orientation of slender plagioclase laths and augite prisms. Laths of plagioclase (An_{60-65}) are 0.2 mm long and constitute about 60 percent of the rock. Augite prisms are 0.1–0.3 mm long and 0.05–0.1 mm thick and make up about 38 percent of the rock. Magnetite (2 percent) in small euhedral to subhedral crystals is ubiquitous. In structure, texture, color, and mineralogy, this basalt resembles the hypersthene andesite on Table Mountain.

In the fine-grained andesite on Table Mountain in the southeast corner of the Bucks Lake quadrangle, hypersthene and augite occur in about equal amounts. Turner (1898) described and illustrated this rock, commenting that the only other locality where hypersthene was found is 0.6 miles southwest of Mount Ararat. The hypersthene andesite on Table Mountain is a light-gray dense rock that has an almost horizontal closely spaced joint system. In this rock, plagioclase (An_{37-40}) is the major constituent (about 70 percent), orthopyroxene and clinopyroxene constitute about 20 percent, and magnetite is an accessory mineral. Some interstitial glass is common.

PLAGIOCLASE BASALTS IN THE PULGA QUADRANGLE

Basalt in the northwest corner of the Pulga quadrangle is continuous with the Lassen Peak volcanic rocks of Pliocene age (Lydon and others, 1960). Most of this basalt is fine grained and vesicular, with only a few small phenocrysts of augite and olivine. Groundmass is very fine grained and consists of tiny laths of plagioclase, grains of augite, and magnetite.

Glomeroporphyritic coarse-grained basalt is exposed on Last Chance Creek (loc. 1141) on the east border of the above occurrence. Thin sections show that the large clustered plagioclase (An_{55-65}) phenocrysts are complexly twinned and very weakly zoned. Small inclusions of augite, magnetite, and hematite are common along the rims and cleavage planes. Augite and olivine phenocrysts are few and small. Groundmass has a near-ophitic texture consisting mainly of plagioclase laths and interstitial augite with some magnetite and olivine.

A very similar glomeroporphyritic basalt is exposed east and northeast of Table Mountain in the north-central part of the Pulga quadrangle, in the area shown as Tertiary basalt on the Chico sheet. In this vicinity five to six successive flows are exposed as terraces. The lowest flow extends northward to the vicinity east of Campbell Lake, where it overlies the northern border zone of Grizzly pluton and its metasedimentary wall-rocks. A similar glomeroporphyritic basalt, shown as Pliocene on the Chico sheet, is exposed north of Jones Meadows and to the northeast in the southern part of the Jonesville quadrangle, as shown on the Westwood sheet (Lydon and others, 1960). In all these localities, plagioclase phenocrysts are large and clustered, whereas the augite and olivine phenocrysts are few and small.

The basalt in the vicinity of Murphy Flat and Ben Lomond is fine grained, resembling the groundmass in the glomeroporphyritic basalt. A few tiny phenocrysts of plagioclase, olivine, and augite are embedded in a fine-grained groundmass of tiny laths of plagioclase and small grains of augite and magnetite.

TERTIARY UNCONSOLIDATED MATERIALS

Glacial deposits. — Glacial moraine material forms several rounded ridges on the northeast slopes of Spanish Peak and Mount Pleasant and in the vicinity of Silver Lake, where numerous round boulders of mainly hornblende-biotite quartz diorite are embedded in unsorted sandy material. Glaciated surfaces of hornblende-biotite quartz diorite and hornblende-pyroxene diorite are well exposed at higher elevations above these ridges. Smaller deposits of glacial debris occur on the north slope of Grizzly Mountain and on the east slope of Dogwood Peak. Morainal material is also widespread at higher elevations in the north-central part of the Pulga quadrangle, especially near Crane Valley and North Valley. Some of these deposits have been washed for gold and have yielded moderate amounts.

Lake deposits.—Meadow Valley is underlain by lake deposits (gravel and sand) that in places carry gold. Gopher Hill gravel on Spanish Creek has been mined intermittently since the last century. Lake beds extend toward Snake Lake in the northeast and toward the southeast to ridges on both sides of Deer Creek. These gravels have been mined hydraulically at many places; they were described by Turner (1898).

Pleistocene river gravels and some undivided gravel deposits. — Old river gravels occur at high elevations along rivers at many places, as for instance at Rich Bar on the East Branch of the North Fork of the Feather River and at Hartman Bar, Butte Bar, and elsewhere on the Middle Fork of the Feather River (not shown on pl. 2). Most of these old gravel bars have been washed for gold. Rich Bar was the most productive. Rusted parts of hydraulic equipment abandoned in the steep canyon of the Middle Fork mark many old mining sites. Some of the gravel deposits are old deposits that have been reworked, as for example much of the gravel along Spanish Creek near Gopher Hill (sec. 12, T. 24 N, R. 8 E.) and to the south.

SUMMARY AND CONCLUSIONS

The Pulga and Bucks Lake quadrangles lie at the north end of the western metamorphic belt of the Sierra Nevada. The Melones fault and accompanying serpentine belt divide the area into two parts with different lithologic sequences on either side. The metamorphic rocks northeast of the serpentine belt are continuous with the Shoo Fly Formation in the adjoining areas. Correlation of the metasedimentary and metavolcanic rocks southwest of the Melones fault is uncertain because of profound deformation and recrystallization that have destroyed the fossil evidence. The major belt of the metasedimentary rocks southwest of the Melones fault, the Calaveras Formation, consists of interbedded metachert and phyllite indicating a marine environment during the deposition. Lying unconformably on the Calaveras Formation, and faulted against it in the southwest, are metavolcanic rocks consisting of meta-andesite, metadacite, and metamorphosed sodarhyolite (the Franklin Canyon Formation) in the eastern part of the area and metabasalt and metarhyolite (the Duffey Dome Formation) in the western part. Pillow structures occur locally in the lower part of the Franklin Canyon Formation, which is believed to be the older of the two formations, but most of the metavolcanic rocks show well-preserved pyroclastic structures, including tuffaceous layers. Southwest of the metavolcanic belt and separated from it by a fault is a sequence of interbedded metavolcanic and metasedimentary rocks called the Horseshoe Bend Formation. This formation occupies a synclinorium between two major faults and includes metavolcanic rocks that are similar to those in the Franklin Canyon and Duffey Dome Formations. Discontinuous layers of phyllite, quartzite, metachert, and limestone are interbedded.

Correlation of these three pyroclastic formations with sections of the metasedimentary and metavolcanic formations farther south and with the Paleozoic section of the Taylorsville area across the Melones fault was attempted on lithologic grounds. Assuming that volcanic activity of similar nature was widespread, the pyroclastic sequences interbedded with the Paleozoic metasedimentary rocks are tentatively correlated with lithologically similar pyroclastic rocks farther south, that is with the Tightner Formation of Ferguson and Gannett (1932) and of Chandra (1961) and with the Devonian to Permian pyroclastic sequence of the Taylorsville area (McMath, 1966).

Two age groups of intrusive rocks are present in the area. The older rocks are closely associated with metavolcanic rocks and represent the deep-seated equivalents of metabasalt, meta-andesite, metadacite and metamorphosed sodarhyolite. They range in composition from hornblendite and metagabbro through metadiorite to metatrondhjemite. The mineral assemblages in the metaigneous rocks are similar to those in the equivalent metavolcanic rocks; the only difference is in texture. The younger intrusive rocks form plutons that have foliated quartz dioritic border zones and that with but one exception grade to massive monzotonalite at their centers. The exception is the Bucks Lake pluton, which includes a large mass of pyroxene diorite in its central part. The chemical composition and the trace-element content of this pyroxene diorite, together with the structural relations, indicate that it is an early differentiate of the same magma from which the quartz dioritic border zone crystallized. The potassium-argon age for the pyroxene diorite is, according to Grommé, Merrill, and Verhoogen (1967), 143 m.y., whereas the quartz dioritic border zones of the Bucks Lake, Grizzly, and Merrimac plutons range from 140 to 130 m.y. in age.

Two episodes of deformation and metamorphism are indicated by structures and sequence of recrystallization in the metamorphic rocks. During the first episode the rocks were isoclinally folded on northwest-trending axes and acquired a strong foliation parallel to the axial planes. A second folding and recrystallization accompanied the emplacement of the Late Jurassic and Early Cretaceous plutons. Steeply plunging lineations and intricate folding around steep second axes are strongest near the plutons and resulted from shouldering of the wallrocks aside by the invading magma.

Generally muscovite, chlorite, and biotite crystallized in the phyllitic layers, and epidote, actinolite, and chlorite crystallized in the metavolcanic rocks during the first episode of metamorphism, indicating a metamorphic grade between the greenschist and epidote-amphibolite facies. The metamorphic grade is higher around the plutons, as shown by coarsening of the grain size and by the mineral assemblages, such as biotite-garnet, staurolite-andalusite, and cordierite-anthophyllite, which are typical of the higher part of the epidote-amphibolite facies. Sillimanite was found only in one locality—the canyon of Bear Creek south of the Bucks Lake pluton, where it occurs with andalusite and cordierite. Elsewhere andalusite and cordierite crystallized next to the intrusive rocks, and in places there are pseudomorphs of yellow mica after staurolite. Staurolite was stable with andalusite farther from the contact. The amount of biotite increases and that of muscovite decreases toward the plutonic rocks. Chlorite is generally absent near the contacts or, if present, is a product of later alteration. These relations indicate that pressure during the second episode of metamorphism was lower than that at which staurolite can coexist with sillimanite. The temperature next to the plutons was higher than that of the upper stability boundary of staurolite.

The ultramafic rocks differ strikingly in composition and trace-element content from the other intrusive rocks and thus must have had a different origin. They have features characteristic of Alpine-type peridotite-serpentine masses most closely resembling those of mantle origin by Wyllie's (1969) classification. They do not have the high-temperature contact aureoles that emplacement of liquid magma or hot crystal mush would produce. On the basis of their texture and mineralogy, they were probably emplaced as a moderate- to low-temperature crystal accumulate which, in its early stages, had only about 10 percent interstitial hydrous basic liquid. The early serpentine minerals, which fill interstices and tiny irregular cracks, may have precipitated from this liquid, which could have greatly facilitated the emplacement along and near the fault zones. The tiny early cracks were formed by microbrecciation at an early stage, most likely during the upward movement of the masses. The regional structures, such as crude foliation and cross joints accompanied by second serpentinization, are clearly overprinted on these early features.

The second stage of serpentinization of the ultramafic bodies is intimately associated with the metamorphic events. These two phenomena were not only concurrent but also chemically complementary in respect to outflowing and inflowing components: H_2O and CO_2 released by the metasedimentary rocks during metamorphism are the very components that invaded the ultramafic masses during their serpentinization. As a consequence of serpentinization, calcium migrated out, forming calc-silicates at the contact and in the silicic masses within the ultramafic bodies. The excess silica from these masses migrated into the serpentine and reacted to form talc. The system as a whole may have operated isochemically, and the amount of available H_2O may have been a controlling factor in the degree of serpentinization.

REFERENCES CITED

Althaus, Egon, 1967, The triple point andalusite-sillimanite-kyanite: Contr. Mineralogy and Petrology, v. 16, no. 1, p. 29–44.

Averilll, C. V., 1937, Mineral resources of Plumas County: California Jour. Mines and Geology, v. 33, no. 2, p. 79–143.

Bateman, P. C., Clark, L. D., Huber, N. K., Moore, J. G., and Rinehart, C. D., 1963, The Sierra Nevada Batholith, a synthesis of recent work across the central part: U.S. Geol. Survey Prof. Paper 414–D, 46 p.

Bateman, P. C., and Eaton, J. B., 1967, Sierra Nevada Batholith; the batholith was generated within a synclinorium: Science, v. 158, no. 3807, p. 1407–1417.

Bateman, P. C., and Wahrhaftig, Clyde, 1966, Geology of the Sierra Nevada, *in* Bailey, E. H., ed., Geology of northern California: California Div. Mines and Geol. Bull. 190, p. 107–172.

Burnett, J. L., and Jennings, C. W., 1962, Geologic map of California, Olaf P. Jenkins edition, Chico Sheet: California Div. Mines and Geology, scale 1:250,000.

Burri, Conrad, 1964, Petrochemical calculations: New York, Daniel Davey & Co., Inc., 304 p.

Cerny, P., 1968, Comments on serpentinization and related metasomatism: Am. Mineralogist, v. 53, nos. 7 and 8, p. 1377–1385.

Chandra, D. K., 1961, Geology and mineral deposits of the Colfax and Foresthill quadrangles, California: California Div. Mines Spec. Rept. 67, 50 p.

Clark, L. D., 1964, Stratigraphy and structure of part of the western Sierra Nevada metamorphic belt, California: U.S. Geol. Survey Prof. Paper 410, 70 p.

Clark, L. D., Imlay, R. W., McMath, V. E., and Silberling, N. J., 1962, Angular unconformity between Mesozoic and Paleozoic rocks in the northern Sierra Nevada, California, *in* Geological Survey research 1962: U.S. Geol. Survey Prof. Paper 450–B, p. B15–B19.

Compton, R. R., 1955, Trondhjemite batholith near Bidwell Bar, California: Geol. Soc. America Bull. v. 66, no. 1, p. 9–44.

Condie, K. C., Barsky, C. K., and Mueller, P. A., 1969, Geochemistry of Precambrian diabase dikes from Wyoming: Geochim. et Cosmochim. Acta, v. 33, p. 1371–1388.

Creely, R. S., 1965, Geology of the Oroville quadrangle, California: California Div. Mines Bull. 184, 86 p.

Dalrymple, G. B., 1964, Cenozoic chronology of the Sierra Nevada, California: California Univ. Pub. Geol. Sci., v. 47, p. 1–41.

Diller, J. S., 1908, Geology of the Tayorsville region, California: U.S. Geol. Survey Bull. 353, 128 p.

Durrell, Cordell, 1959a, Tertiary stratigraphy of the Blairsden quadrangle, Plumas County, California: California Univ. Pub. Geol. Sci., v. 34, no. 3, p. 161–192.

———1959b, The Lovejoy Formation of northern California: California Univ. Pub. Geol. Sci., v. 34, no. 4, p. 193–220.

———1966, Tertiary and quaternary geology of the northern Sierra Nevada, *in* Bailey, E. H., ed., Geology of northern California: California Div. Mines Bull. 190, p. 185–197.

Durrell, Cordell, and Proctor, P. D., 1948, Iron-ore deposits near Lake Hawlay and Spencer Lakes, Sierra County, California: California Div. Mines Bull. 129, pt. L, p. 165–192.

Evans, B. W., 1965, Application of a reaction-rate method to the breakdown equilibria of muscovite and muscovite plus quartz: Am. Jour. Sci., v. 263, p. 647–667.

Evernden, J. F., and James, G. T., 1964, Potassium-argon dates and the Tertiary floras of North America: Am. Jour. Sci., v. 262, no. 8, p. 945–974.

Evernden, J. F., and Kistler, R. W., 1970, Chronology of emplacement of Mesozoic batholithic complexes in California and western Nevada: U.S. Geol. Survey Prof. Paper 623, 42 p.

Ferguson, H. G., and Gannett, R. W., 1932, Gold quartz veins of the Allegheny district, California: U.S. Geol. Survey Prof. Paper 172, 139 p.

Fiske, R. S., Hopson, C. A., and Waters, A. C., 1963, Geology of Mount Rainier National Park, Washington: U.S. Geol. Survey Prof. Paper 444, 93 p.

Ganguly, J., and Newton, R. C., 1968, Thermal stability of chloritoid at high pressure and relatively high oxygen fugacity: Jour. Petrology, v. 9, no. 3, p. 444–466.

Grommé, C. S., Merrill, R. T., and Verhoogen, John, 1967, Paleomagnetism of Jurassic and Cretaceous plutonic rocks in the Sierra Nevada, California, and its significance for polar wandering and continental drift: Jour. Geophys. Research, v. 72, no. 22, p. 5,661–5,684.

Hietanen, Anna, 1951, Metamorphic and igneous rocks of the Merrimac area, Plumas National Forest, California: Geol. Soc. America Bull., v. 62, no. 6, p. 565–608.

———1961, A proposal for clarifying the use of plutonic calc-alkalic rock names, in short papers in the geologic and hydrologic sciences: U.S. Geol. Survey Prof. Paper 424–D, p. D340–D342.

———1963, Idaho batholith near Pierce and Bungalow, Clearwater County, Idaho: U.S. Geol. Survey Prof. Paper 344–D, 42 p. [1964].

———1967, On the facies series in various types of metamorphism: Jour. Geology, v. 75, no. 2, p. 187–214.

———1968, Belt Series in the region around Snow Peak and Mallard Peak, Idaho: U.S. Geol. Survey Prof. Paper 344–E, 34 p.

———1969, Distribution of Fe and Mg between garnet, staurolite, and biotite in aluminum-rich schist in various metamorphic zones north of the Idaho Batholith: Am. Jour. Sci., v. 267, no. 3, p. 422–456.

———1972, Tertiary basalts in the Feather River area, California, *in* Geological Survey research 1972: U.S. Geol. Survey Prof. Paper 800–B, p. B85–B94.

Hoschek, G., 1967, Zur unteren Stabilitätsgrenze von Staurolith: Naturwissenschaften, 54 Jahrg. H. 8, p. 200–201.

———1968, Zur oberen Stabilitätsgrenze von Staurolith: Naturwissenschaften, 55 Jahrg., H. 5, p. 226–227.

Johannsen, Albert, 1951, A descriptive petrography of the igneous rocks, v. 4: Chicago, Ill., University of Chicago Press, 523 p.

———1952, A descriptive petrography of the igneous rocks; v. 2: Chicago, Ill., University of Chicago Press, 428 p.

Lawson, A. C., 1903, Plumasite, an oligoclase-corundum rock near Spanish Peak, California: California Univ. Pub. Geol. Sci., v. 3, no. 8, p. 219–229.

Luth, W. C., Jahns, R. H., and Tuttle, O. F., 1964, The granite system at pressures 4 to 10 kilobars: Jour. Geophys. Research, v. 69, p. 759–773.

Lydon, P. A., Gay, T. E., and Jennings, C. W., 1960, Geologic map of California, Olaf P. Jenkins edition, Westwood sheet: California Div. Mines, scale 1:250,000.

MacGinitie, H. D., 1941, A middle Eocene flora from the central Sierra Nevada: Carnegie Inst. Wash. Pub. 534, 178 p.

McMath, V. E., 1958, Geology of the Taylorsville area, Plumas County, Calif.: California Univ. at Los Angeles, Ph. D. thesis.

———1966, Geology of the Taylorsville area, northern Sierra Nevada, *in* Bailey, E. H., ed., Geology of northern California: California Div. Mines and Geology Bull. 190, p. 173–183.

Medaris, L. G., Jr., 1969, Partitioning of Fe^{++} and Mg^{++} between coexisting synthetic olivine and orthopyroxene: Am. Jour. Sci., v. 267, no. 8, p. 945–968.

Moore, J. G., 1963, Geology of the Mount Pinchot quadrangle, southern Sierra Nevada, California: U.S. Geol. Survey Bull. 1130, 152 p.

Moores, E. M., 1970, Pre-batholith structure and stratigraphy of the Lake Almanor and Greenville quadrangles, northern Sierra Nevada—Progress report [abs.]: Geol. Soc. America Abs. with Programs, v. 2, no. 2, p. 121.

Newton, R. C., 1966, Kyanite-sillimanite equilibrium at 750°C: Science, v. 151, no. 3715, p. 1222–1225.

Pabst, Adolf and Stinson, M. C., 1960, Brannerite with gold from Plumas County, California [abs.]: Geol. Soc. America Bull. 71, pt. 2, p. 2,071–2,072.

Page, N. J., 1967, Serpentinization considered as a constant volume metasomatic process; a discussion: Am. Mineralogist, v. 52, nos. 3 and 4, p. 545–549.

Piwinskii, A. J., 1968, Experimental studies of igneous rock series, central Sierra Nevada batholith, California: Jour. Geology, v. 76, no. 5, p. 548–570.

Potbury, S. S., 1935, The LaPorte flora of Plumas County, California: Carnegie Inst. Wash. Pub. 465, p. 29–81.

Pugin, V. A., and Khitarov, N. I., 1968, The Al_2O_3-SiO_2 system at high temperatures and pressures: Geochem. Internat. v. 5, no. 1, p. 120–128.

Richardson, S. W., 1968, Staurolite stability in a part of the system Fe-Al-Si-O-H: Jour. Petrology, v. 9, no. 3, p. 467–488.

Richardson, S. W., Gilbert, M. C., and Bell, P. M., 1969, Experimental determination of kyanite-andalusite and andalusite-sillimanite equilibria; the aluminum silicate triple point: Am. Jour., Sci., v. 267, no. 3, p. 259–272.

Russell, R. J., 1928, Basin Range structure and stratigraphy of the Warner Range, northeastern California: California Univ. Pub. Geology Bull., v. 17, p. 387–496.

Schreyer, Werner, 1967, A reconnaissance study of the system MgO-Al_2O_3-SiO_2-H_2O at pressures between 10 and 25 Kb: Carnegie Inst. Year Book 66, p. 380–392.

Schreyer, Werner, and Yoder, H. S., Jr., 1964, The system Mg-cordierite-H_2O and related rocks: Neues Jahrb. Mineralog. Abh., v. 101, no. 3, p. 271–342.

Thayer, T. P., 1966, Serpentinization considered as a constant-volume metasomatic process: Am. Mineralogist, v. 51, p. 685–710.

Turner, H. W., 1898, Bidwell Bar, California: U.S. Geol. Survey Geol. Atlas, Folio 43.

Tuttle, O. F., and Bowen, N. L., 1958, Origin of granite in the light of experimental studies in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O: Geol. Soc. America Mem. 74, 153 p.

Weill, D. F., 1966, Stability relations in the Al_2O_3-SiO_2 system calculated from solubilities in the Al_2O_3-SiO_2-Na_3Al_6 system: Geochim. et Cosmochim. Acta, v. 30, p. 223–237.

Whittaker, E. J. W., and Zussman, J., 1956, The characterization of serpentine minerals by X-ray diffraction: Mineral Mag., v. 31, no. 233, p. 107–126.

Winchell, A. N., and Winchell, H., 1951, Elements of optical mineralogy—an introduction to microscopic petrography; Part 2, Description of minerals [4th ed.]: New York, John Wiley & Sons, Inc., 551 p.

Wyllie, P. J., 1969, The origin of ultramafic and ultrabasic rocks: Tectonophysics, v. 7, nos. 437–455.

Yoder, H. S., Jr., and Eugster, H. P., 1955, Synthetic and natural muscovites: Geochim. et Cosmochim. Acta, v. 8, nos. 5–6, p. 225–280.

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