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Metamorphism and Plutonism Around the Middle and South Forks of the Feather River, California

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By ANNA HIETANEN

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Petrologic and structural studies of metamorphic and igneous rocks of part of the Nevadan orogenic belt in the northwestern Sierra Nevada

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METAMORPHISM AND PLUTONISM AROUND THE MIDDLE AND SOUTH FORKS OF THE FEATHER RIVER, CALIFORNIA

By Anna Hietanen

ABSTRACT

The area around the Middle and South Forks of the Feather River provides information on metamorphic and igneous processes that bear on the origin of andesitic and granitic magmas in general and on the variation of their potassium content in particular. In the north, the area joins the Pulga and Bucks Lake quadrangles studied previously. Tectonically, this area is situated in the southern part of an arcuate segment of the Nevadan orogenic belt in the northwestern Sierra Nevada. The oldest rocks are metamorphosed calc-alkaline island-arc-type andesite, dacite, and sodarhyolite with interbedded tuff layers (the Franklin Canyon Formation), all probably correlative with Devonian rocks in the Klamath Mountains. Younger rocks form a sequence of volcanic, volcaniclastic, and sedimentary rocks including some limestone (The Horseshoe Bend Formation), probably Permian in age. All the volcanic and sedimentary rocks were folded and recrystallized to the greenschist facies during the Nevadan (Jurassic) orogeny and were invaded by monzotonalitic magmas shortly thereafter. A second lineation and metamorphism to the epidote-amphibolite facies developed in a narrow zone around the plutons.

In light of the concept of plate tectonics, it is suggested that the early (Devonian?) island-arc-type andesite, dacite, and sodarhyolite (the Franklin Canyon Formation) were derived from the mantle above a Benioff zone by partial melting of peridotite in hydrous conditions. The water was probably derived from an oceanic plate descending to the mantle. Later (Permian?) magmas were mainly basaltic; some discontinuous layers of potassium-rich rhyolite indicate a change into anhydrous conditions and a deeper level of magma generation. The plutonic magmas that invaded the metamorphic rocks at the end of the Jurassic may contain material from the mantle, the subducted oceanic lithosphere, and the downfolded metamorphic rocks. The ratio of partial melts from these three sources may have changed with time, giving rise to the diversity in composition of magmas.

INTRODUCTION

Petrologic and structural studies around Middle and South Forks of the Feather River extend the work begun in the Pulga and Bucks Lake quadrangles to the southern part of the northern arcuate segment of the western metamorphic belt of the Sierra Nevada (fig. 1). The study area covers some 750 square kilometres in the southern half of the old Bidwell Bar 30-minute quadrangle (Turner, 1898), now covered by five 7½-minute quadrangles, the Brush Creek, Cascade, American House, Clipper Mills, and Strawberry Valley quadrangles in northern California (figs. 1, 2). The mapped area is between long 121°0′ and 121°22½′, lat 39°30′ and 39°45′, adjoining the Bucks Lake and Pulga quadrangles to the north (Hietanen, 1973a). In the western part, it includes part of the Merrimac area (Hietanen, 1951) and the eastern contact zone of the Bald Rock pluton (Compton, 1955).

Most of the area is underlain by plutonic rocks that include the Cascade pluton, parts of two other large plutons, the Merrimac and Bald Rock, and several small masses. The metamorphic rocks exposed between the plutons are continuous with the metavolcanic and metasedimentary rocks in the Pulga and Bucks Lake quadrangles to the north and the Merrimac area to the west. Subdivision of the metamorphic rocks into three formations, the Calaveras, Franklin

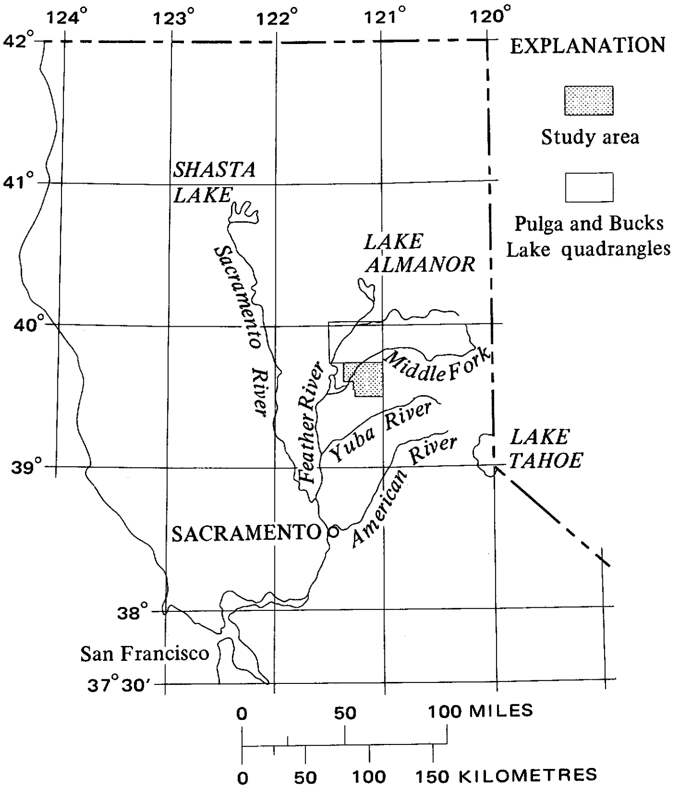

FIGURE 1.—Location of the study area in northern California.

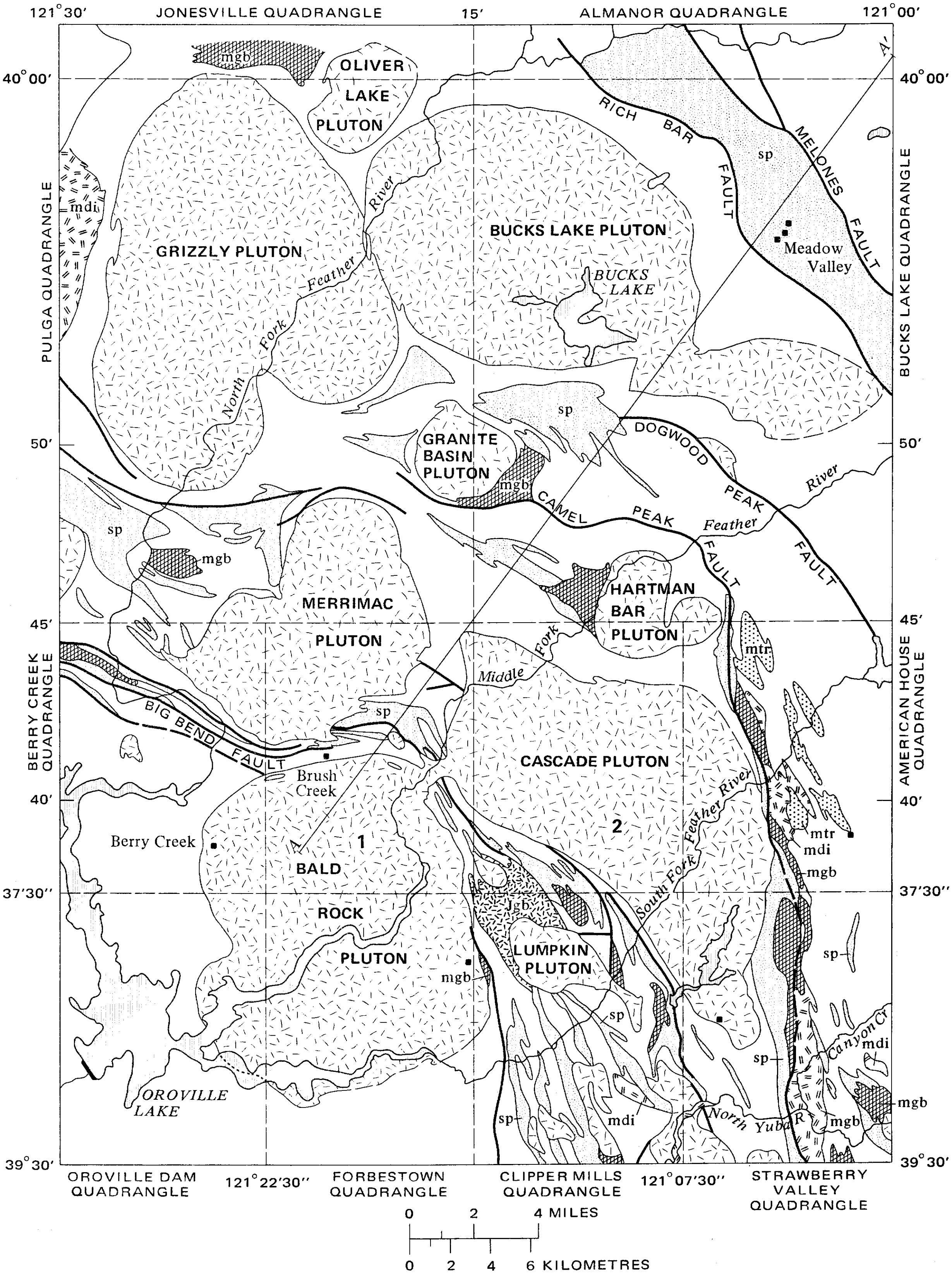

FIGURE 2.—Sketch map and section of the study area and vicinity, northern California.

Canyon, and Horseshoe Bend Formations, was established in the Pulga and Bucks Lake quadrangles to the north (Hietanen, 1973a). Of these only two, the Franklin Canyon and Horseshoe Bend, are exposed in the study area. The higher elevations in the eastern

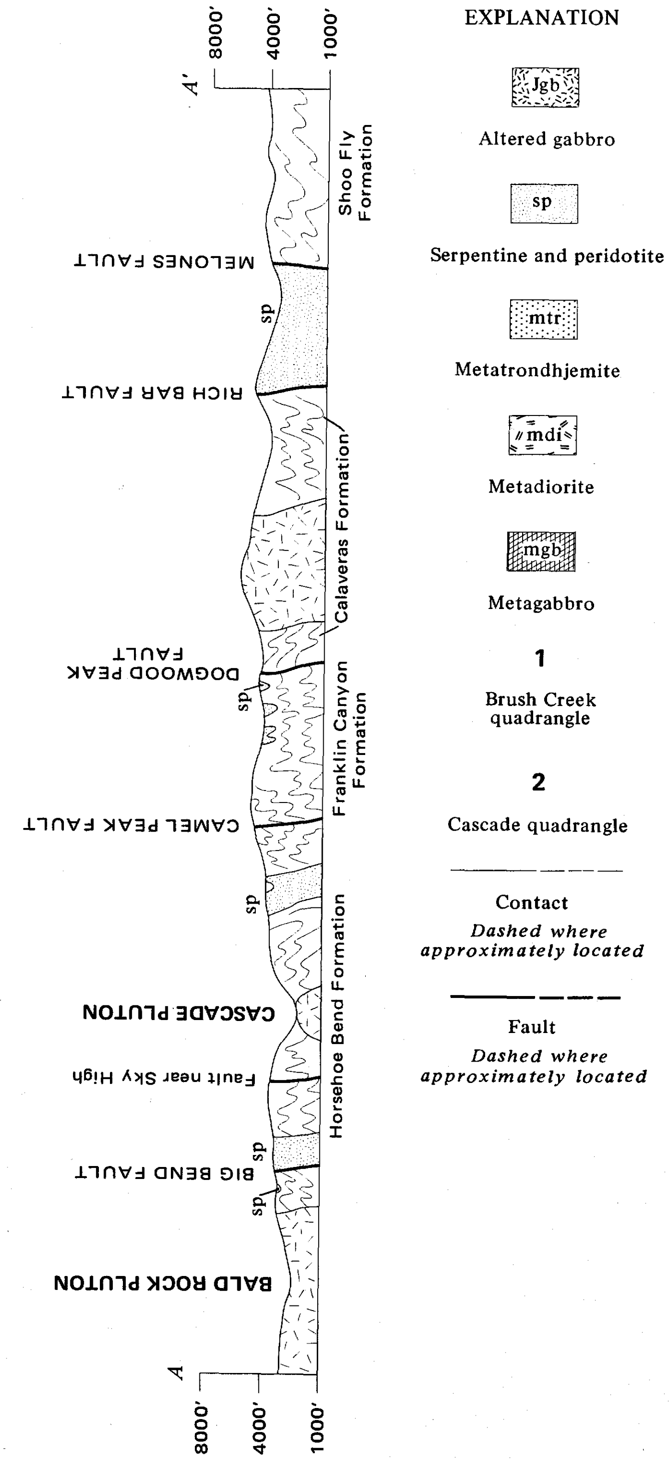

FIGURE 2.—Continued.

part of the area are covered by Tertiary volcanic rocks. These rocks have been described in an earlier report (Hietanen, 1972) and will not be discussed further here.

The major geologic events in the area were as follows: (1) deposition of the Franklin Canyon Formation (Devonian?); (2) deposition of the Horseshoe Bend Formation (Permian?); (3) intrusion of synkinematic quartz diorite and trondhjemite and of ultramafic rocks, subsequent deformation and recrystallization culminating in Jurassic time; (4) continued faulting and emplacement of ultramafic rocks; (5) emplacement of postkinematic plutons (Late Jurassic and Early Cretaceous); (6) uplift and erosion; (7) extrusion of Tertiary volcanic rocks.

GEOLOGIC SETTING

The study area lies in the innermost part of an arcuate segment of the northern Sierra Nevada; structural trends in the metamorphic rocks south of the area are generally northerly, trends north and west of the area, westerly. The trends curve sharply from northerly to westerly around the Hartman Bar pluton just north of the map area and around the Bald Rock pluton in the southwestern part of the area (fig. 2; pl. 1).

Local disruption in the arc is evident southeast of the Hartman Bar pluton where the westerly trends butt against the north-trending segment of the Camel Peak fault concealed by the elongate body of serpentine (fig. 2; pl. 1). This fault, well defined by elongate serpentine bodies (pl. 1), is a contact between two formations, the metavolcanic Franklin Canyon Formation to the northeast and the metasedimentary and the metavolcanic Horseshoe Bend Formation to the southwest.

Another major fault zone, en echelon in part, passes through the metamorphic rocks north and northeast of the Bald Rock pluton where several faults, all accompanied by serpentine bodies, were mapped. The faults and serpentine bodies are older than the youngest of the Cretaceous plutons, as shown by a tongue of trondhjemite that, in the canyon of the Middle Fork of the Feather River, cuts sharply the metamorphic rocks and all their structures (pl. 1). On the northwest side of the river, the fault zone is concealed by serpentine bodies; farther west, two parellel faults pass through a narrow strip of metamorphic rocks between the Bald Rock and Merrimac plutons. This fault zone is the eastern extension of the Big Bend fault (fig. 2). Two parallel faults occupied by thin bodies of serpentine are exposed on Watson Ridge (pl. 1) on the southeast side of the Middle Fork. The southeastern extension of this fault zone continues between the Lumpkin pluton and the Cascade pluton, where it is represented by three faults that are several kilometres long and about 1–2 km apart. The middle branch of this en echelon fault passes on the west side of Sugar Pine Point at the south end of Lumpkin Ridge, where it is marked by a brown-weathering fault gorge, several metres wide, and by local angular discordance of structures. This middle branch terminates at the border of the Lumpkin pluton, and another south-southeast-trending fault accompanied by a long thin body of serpentine is exposed about 1 km east of Sugar Pine Point passing southward to the Lost Creek Reservoir and to the east side of Barton Hill.

Several north-northwest-trending faults and numerous long thin conformable serpentine bodies in the Horseshoe Bend Formation south and southwest of Lumpkin pluton suggest intensive slicing during the deformation in a wide zone east of the Bald Rock pluton. Metavolcanic rocks exposed to the west of the westernmost fault of this zone are less deformed than the rocks of the Horseshoe Bend Formation and are probably Mesozoic in age.

Two major fault zones divide the metamorphic rocks into three belts, each containing rocks of only one formation, from east to west, the Franklin Canyon Formation, the Horseshoe Bend Formation, and the unnamed Mesozoic rocks. In the easternmost belt (pl. 1), east of the Camel Peak fault, the Franklin Canyon Formation is a direct continuation of similar rocks in the Bucks Lake quadrangle (Hietanen, 1973a). The Franklin Canyon consists of potassium-poor metavolcanic rocks—specifically metasodarhyolite, metadacite, meta-andesite, and associated metatuffs. It is probably correlative with the Devonian island-arc-type volcanic rocks in the Klamath Mountains. In the Bucks Lake quadrangle, this formation rests on the metasedimentary Calaveras Formation, which consists of interbedded metachert and phyllite and very little limestone originally similar to sediments deposited on ocean floors.

The formation exposed around the Cascade pluton belongs to the central belt and consists of interbedded volcanic, volcaniclastic, and sedimentary strata including small lens-shaped bodies of marble. These rocks are a southeast extension of the Horseshoe Bend Formation of the Bucks Lake and Pulga quadrangles; structural relations there suggest that they are younger than the metavolcanic rocks of the Franklin Canyon Formation. They may be correlative with the Permian volcanic, volcaniclastic, and shallow-water sedimentary rocks of the Klamath Mountains. This correlation is supported by an occurrence of Permian(?) fossils in similar limestones just west of the study area (Creely, 1965). It is noteworthy that whereas the metarhyolites of the older formation, the Devonian(?) Franklin Canyon, are poor in potassium, some of those of the younger Horseshoe Bend Formation contain a considerable amount of potassium feldspar.

A sequence of metabasalt and metatuff with interbedded metarhyolite, quartzite, and phyllite exposed north and east of the Bald Rock pluton in the southwestern part of the central belt is similar to parts of the Horseshoe Bend Formation. It also resembles a similar sequence in the Pulga quadrangle, where it was distinguished as the Duffey Dome Formation (Paleozoic?) underlying the metasedimentary rocks of the Horseshoe Bend Formation. On the geologic map (pl. 1) this sequence is included in the Horseshoe Bend Formation.

The metavolcanic rocks bordering the Bald Rock pluton to the southeast are similar to the Mesozoic rocks southwest of the map area. Detailed description of these rocks is not included in this report. The boundary between the Paleozoic rocks of the Horseshoe Bend Formation and the Mesozoic rocks to the southwest probably lies in part along the northern and eastern contact of the Bald Rock pluton. The northern contact zone of this pluton is strongly sheared and in alinement with a long thin body of serpentine and talc schist in the Big Bend area (Hietanen, 1951). This lineament is 1 km south of the Big Bend fault and may represent a southern branch of this fault.

In each of the fault blocks, geographically defined by the three belts, the metasedimentary and metavolcanic rocks are isoclinally folded; the folds in general are overturned to the southwest. In the easternmost belt, the axes of major folds plunge 25°–45° to the southeast, and there is a strong lineation parallel to the axes. In the central belt, the early southeasterly structural trends have been modified by the Cascade, Merrimac, and Hartman Bar plutons. Lineation around the northwestern end of the Cascade pluton plunges to the northeast, at right angle to that in the eastern belt. A second folding around this northeast lineation is strongly developed between the Cascade and Merrimac plutons, where the rocks of the Horseshoe Bend Formation were squeezed at right angles to the preplutonic trends and refolded around the northeast axes. Distribution of the rock types on the northeast side of the Cascade pluton indicates that the major folds, strongly overturned to the southwest, are on the southeast-plunging axes. The attitude of bedding planes and the easterly plunge of lineation in the narrow belt of metamorphic rocks between the Cascade and Bald Rock plutons also indicates overturning to the southwest.

These structural relations are shown in a northeastward-trending cross section from Bald Rock pluton across the Melones fault into the Shoo Fly Formation at the northeast corner of the Bucks Lake quadrangle (fig. 2). The movement along each of the five faults—Melones, Rich Bar, Dogwood Peak, Camel Peak, and Big Bend—was down on the southwest side, supporting the hypothesis of subduction along the late Paleozoic and early Mesozoic continental margin, as suggested by Burchfiel and Davis (1972). The five faults can be interpreted as Mesozoic surface features of the subduction that earlier (during the Paleozoic) gave rise to an extensive island-arc-type volcanism in this area. With few exceptions, the faults are preplutonic, as shown by sharp crosscutting relations in the canyon of the Middle Fork of the Feather River south of American Bar.

In age, the plutons average 130 million years (Grommé and others, 1967); the older plutons are in the eastern part. The largest is the composite Cascade pluton, which, partly covered by Tertiary volcanic rocks, underlies an area of about 195 square kilometres in the central part of the area (pl. 1). Parts of the Merrimac and Bald Rock plutons are exposed in the westernmost part of the area, and the southern part of the Hartman Bar pluton is along the northern border of the area. The conformable contacts of the Cascade pluton and its elongate curved shape that conforms with the arc in the trends of the metamorphic rocks suggests that this pluton was emplaced somewhat earlier than the Merrimac and Bald Rock plutons. This is confirmed by a tongue of younger trondhjemitic rocks that extends from the Bald Rock pluton to the Cascade pluton, cutting its structures discordantly. Two small masses of altered diorite, the Lumpkin pluton and a mass at Frey Creek exposed between the Cascade and Bald Rock plutons, are probably somewhat older than the Cascade pluton. They consist of diorite that is more thoroughly recrystallized than the quartz diorite in the large plutons. A small mass of trondhjemite at Shute Mountain is similar to the trondhjemite in the Bald Rock pluton and is probably an offshoot of the same magma.

The Cascade pluton was emplaced in an anticlinorium (sections *A–A′* and *B–B′*), the broken apex of which is near Sky High in the northwestern part of the area of plate 1 and the western limb of which was squeezed between the Cascade and Merrimac plutons and refolded around northeast-trending axes. Generally the trends curve around the plutons, giving an impression of the shouldering effect of the invading magma. The details of the structural features are given after the petrographic description of the rocks.

METAVOLCANIC AND METASEDIMENTARY ROCKS

The lithology and petrography of the metavolcanic Franklin Canyon Formation and the interbedded metasedimentary and metavolcanic rocks of the Horseshoe Bend Formation are similar to lithology and petrography of these formations in the Pulga and Bucks Lake quadrangles (Hietanen, 1973a). Therefore only a brief description is given in this paper, the emphasis being on differences rather than similarities.

FRANKLIN CANYON FORMATION

The Franklin Canyon Formation—considered Devonian(?) in age—consists of meta-andesite, metadacite, metasodarhyolite, metatuff, and a small amount of phyllite. In its western part, it is mainly interlayered metadacite and metasodarhyolite that contain some interbedded metatuff. In its eastern part, a thick layer of andesitic metatuff is overlain by meta-andesite that includes thick flows, many showing pillow structures. The structural relations suggest that metadacite and interbedded metasodarhyolite are older and in part faulted against the meta-andesitic rocks. In the east-central part of the study area (pl. 1)—near American House and along Slate Creek—and to the south, thick discontinuous layers of fine-grained black phyllite are interbedded with andesitic metatuff. Thinner discontinuous layers of similar phyllite are interbedded with metatuff farther north along Lost Creek and its tributaries. These layers have well-preserved bedding that helped in mapping the structure. A few thin layers of metachert not shown on the map are interbedded with metatuff. South of American House and along Slate Creek, the andesitic metatuff grades through tuffaceous metasediment into black phyllite. Fragments of this phyllite and metatuff—well exposed in the canyon of Slate Creek—in overlying mafic meta-andesite prove that the meta-andesite is younger. A few discontinuous thin layers of granular gray quartzite are interbedded with phyllite and metavolcanic rocks in the southeastern corner of the area.

The mafic meta-andesite along Simon Ravine and Gold Run is coarser grained than meta-andesite elsewhere, suggesting a thicker flow or closeness of a former vent. The existence of a vent is supported by the occurrence of swarms of inclusions of black phyllite in meta-andesite in the gorge of Gold Run. The individual fragments in these swarms, in length a fraction of a centimetre to several metres, are from a layer of black phyllite that extends southward to Simon Ravine and beyond. This phyllite is underlain by metatuff on the west and bounded by a fault on the east. Some small rounded fragments of metatrondhjemite—presumably a deep-seated equivalent of metamorphosed soda-rhyolite—are included in the coarse-grained meta-andesite along Simon Ravine, supporting the relative ages inferred from the structures of the older silicic western and somewhat younger andesitic eastern part of this belt.

Metadacite is a fine-grained greenish-gray rock in which some quartz can be identified with a hand lens. In many layers volcanic bombs and other pyroclastic structures similar to those described from the Bucks Lake quadrangle (Hietanen, 1973a) are common, indicating the explosive character of the eruptions. Thin sections show that most metadacite contains phenocrysts of albite and occasionally some quartz embedded in the groundmass that consists of albite, actinolite, green hornblende, chlorite, epidote, clinozoisite, quartz, sparse biotite, leucoxene, magnetite, and pyrite. Albite includes numerous tiny crystals of actinolite, epidote minerals, and some muscovite. Vesicles are filled by quartz. Amphibole prisms, many consisting of green hornblende with pale actinolitic ends, are either randomly oriented or show a weak parallel orientation. The interbedded tuffaceous layers have the same mineralogy but are clearly schistose. Many layers have fine-grained lapilli consisting of a mixture of sericite plus epidote.

Metasodarhyolite is lighter in color than the metadacite and contains more quartz and albite. Thin sections show that quartz and albite occur as phenocrysts; the albite includes numerous tiny grains of epidote and muscovite. Groundmass consists of quartz, albite, chlorite, and muscovite with or without biotite or actinolite. Leucoxene and magnetite are common accessory minerals. Interbedded tuffaceous layers are rich in quartz and muscovite and contain some chlorite, biotite, epidote, leucoxene, magnetite, and hematite. Large granulated phenocrysts of quartz are common.

Meta-andesite is a medium greenish-gray fine-grained tough-to-break rock in which no quartz can be seen under a hand lens. Clean outcrops along the rivers reveal both pyroclastic and pillow structures. Thin sections show that meta-andesite consists mainly of epidote minerals, green hornblende, actinolite, albite, and chlorite in varying proportions. Sphene, leucoxene, magnetite, and pyrite are common accessory minerals. In places, quartz occurs in small round grains and secondary veinlets.

Phenocrysts in the original andesite were pyroxene, hornblende, or plagioclase or any two of these minerals. Most of the pyroxene phenocrysts have been altered to chlorite with some sphene or to chlorite and actinolite. In a few places, as at the Little Grass Valley Dam, phenocrysts of pyroxene are well preserved in massive parts of the flows and in centers of pillows. These phenocrysts, rimmed by chlorite, are embedded in a thoroughly recrystallized groundmass consisting mainly of epidote and amphiboles.

Euhedral phenocrysts of hornblende, 1–6 mm long, occur in meta-andesite on the South Fork of the Feather River about 1 km below the Little Grass Valley Dam and to the south. The pleochroism of the hornblende in the phenocrysts is γ=brownish green, β=green, α=pale yellowish green; green to pale-green hornblende occurs as an alteration product. Pyroxene has been pseudomorphosed to aggregates of actinolite + chlorite. Actinolite forms slender prisms that show parallel orientation and are separated by a mesh of fine-grained chlorite. Former plagioclase phenocrysts consist of epidote + albite. Groundmass is a fine-grained mixture of epidote, actinolite, hornblende, and albite.

Phenocrysts of albite, 0.5–1.5 mm long, are common in meta-andesite at Lexington Hill. Ferromagnesian minerals in this rock are chlorite and hornblende. Some aggregates of chlorite include small grains of epidote and show outlines of former pyroxene crystals. Most epidote forms large aggregates irregular in outline, but some grains are scattered. Many small fractures are filled by epidote crystals and quartz. Small amounts of quartz in tiny euhedral grains, in small oval aggregates, and as a fracture filling are common.

The meta-andesite, some with pillow structure and some with augite phenocrysts, is rich in calcium (most of it contained in epidote), iron, and magnesium, and poor in silicon (Hietanen, 1973a) and can be best classified as basaltic meta-andesite. It is intimately associated with metadacite and metamorphosed sodarhyolite and with more silicic meta-andesites containing hornblende and plagioclase phenocrysts, all these rocks being differentiates of a potassium-poor andesitic magma.

Most of the andesitic metatuff is distinctly bedded, the fine-grained dark-gray layers, 0.2–5 cm thick, alternating with brownish-gray coarse-grained layers of the same thickness. Contacts between the beds are usually gradational in both directions. Graded bedding is rare and can seldom serve as a marker for the tops of the beds.

Thin sections show that in the coarse-grained layers angular to lens-shaped lithic fragments consisting of albite, epidote, actinolite, quartz, and muscovite in various proportions are embedded in matrix that consists mainly of epidote and actinolite. Some euhedral to subhedral prisms of brownish-green hornblende, subhedral grains of altered plagioclase and quartz, are scattered in the matrix. Leucoxene and magnetite are common accessory minerals. The fine-grained layers consist mainly of albite, epidote, and actinolite with 5–10 percent quartz and some chlorite and muscovite.

Layers of tuffaceous metasediments that are interbedded with metatuffs contain more quartz and micaceous minerals and less epidote and actinolite than the normal metatuffs. Scattered fragments of quartz and altered phenocrysts of plagioclase and hornblende are common.

All black phyllite is fine grained, distinctly bedded, and has a strong *b* lineation. The major constituents are round to angular grains of quartz and some albite in a fine-grained matrix of quartz, albite, muscovite, chlorite, biotite, epidote minerals, leucoxene, magnetite, and hematite. The dark color is imparted by disseminated magnetite in the matrix. The lighter colored layers are generally coarser grained and contain less magnetite. These phyllite layers are most likely sedimentary in origin.

Quartzite in the southeastern corner of the area is thin bedded. Layers 1–5 cm thick of this light-gray granular quartzite are separated by micaceous laminae or interbedded phyllite.

HORSESHOE BEND FORMATION

The Horseshoe Bend Formation—considered Permian(?) in age—is exposed all around the Cascade pluton. In the north, a zone of the Horseshoe Bend about 1½ km wide separates the Hartman Bar pluton from the Cascade pluton. Toward the east, the Horseshoe Bend Formation butts against the Camel Peak fault for a distance of 2 km (fig. 2; pl. 1), and farther south only a thin discontinuous strip of the Horseshoe Bend is exposed between the pluton and serpentine that accompanies this fault to the southern border of the map area (pl. 1). On the west side of the pluton, the Horseshoe Bend Formation is exposed between the Cascade and Merrimac plutons and, farther south, between the Cascade and Bald Rock plutons. The Lumpkin pluton was emplaced into this formation.

The Horseshoe Bend Formation consists of interbedded metasedimentary and metavolcanic rocks. The metasedimentary rocks are quartzite and phyllite with discontinuous layers of marble. The metavolcanic rocks are mainly metabasalt and metatuff with interbedded discontinuous layers of meta-andesite, metadacite, and metarhyolite, all more extensive and more numerous in the northern and southern parts of the area than in the central part, where only a few thin discontinuous layers of metarhyolites are present.

Stratigraphy of the formation is difficult to establish because the rocks are tightly folded, overturned, and faulted. Distribution of the rock types and the attitude of bedding near Marble Cone along the Middle Fork of the Feather River north of the Cascade pluton suggest that the metasedimentary units on either side of the meta-andesite–metadacite unit belong to the same layer. The marble dips gently (30°–60°) under the volcanic unit, whereas dips in the metasedimentary unit above are steep (70° to vertical). These structural features indicate a syncline overturned to the southwest (cross section *B–B′*, pl. 1). The quartzite-phyllite unit on the northeast side contains several thin discontinuous marble layers that may be lateral extensions of the thick marble layer at Marble Cone. Thin layers of metatuff and metabasalt underlie the interbedded quartzite-phyllite unit that includes marble lenses. Another unit of metabasalt, stratigraphically in the upper part of the formation, overlies the phyllite southeast of the Hartman Bar pluton.

A similar sequence is exposed between the Cascade and Merrimac plutons and continues therefrom to the southeast between the Cascade and Bald Rock plutons. The metabasalt unit exposed at Shute Mountain and vicinity is overlain by a thick sequence of interbedded quartzite and phyllite that includes discontinuous layers of white to gray marble. The tops of the beds as well as the plunge of the fold axes along the Little North Fork are to the northeast. Some thin layers of metatuff and lens-shaped bodies of metadacite and metarhyolite also are interbedded. The depositional sequence is interrupted by faults near Sky High, and it seems likely that the northern part of the section is overturned. If it is, the metabasalt at the northern border of the area is equivalent to the metabasalt unit at Shute Mountain, and the thick layer of white to gray marble exposed in the canyon of the Little North Fork west of Sky High might be in the same stratigraphic horizon as the marble at Milsap Bar and its counterpart near the mouth of the Little North Fork.

The extension of the Horsehoe Bend Formation between the Bald Rock and Cascade plutons south of the dikelike body of trondhjemite that cuts through this narrow zone of metamorphic rocks consists of rock types similar to those exposed north of the trondhjemite but contains only a few thin calcite-bearing layers. The metabasalt just east of the Bald Rock pluton north of Feather Falls is equivalent to the metabasalt at Shute Mountain and is overlain by interbedded quartzite and phyllite that include tuffaceous beds and discontinuous layers of metabasalt, metarhyolite, and meta-andesite. This sequence continues southward to the west side of the southern tip of the Cascade pluton, where a quartzite and phyllite unit is overlain by basaltic metatuff and metabasalt.

The western part of the section south of the Lumpkin pluton is probably thickened by several faults and may include rocks younger than the Horseshoe Bend Formation. This section is well exposed along the deep gorge of the South Fork of the Feather River and on the roadcuts south of it. Several long thin bodies of serpentine in this section were probably emplaced along the faults, a concept supported by the repetition of sequences of quartzite, phyllite, and metavolcanic rocks in narrow zones between these serpentine bodies. Metavolcanic rocks in the southernmost part of the area are similar to those along the northern boundary. Small lenseshaped bodies of meta-andesite, metadacite, and metarhyolite occur with metatuffs and metabasalt. Potassium feldspar content of metarhyolites ranges from negligible to about 10 percent.

The deposition of the Horseshoe Bend Formation seems to have begun with basaltic volcanism, followed by a quiet period during which sediments that produced quartzite, phyllite, and marble were laid down. A second episode of volcanism followed and was periodically interrupted long enough to allow intervening sedimentation.

It is probable that the lower metabasalt unit north and east of the Bald Rock pluton is equivalent to the metabasalt exposed in the central part of the Pulga quadrangle called the Duffey Dome Formation (Hietanen, 1973a). This formation, like the metabasalt exposed between the Merrimac and Bald Rock plutons, includes some quartzite, metatuff, and metarhyolite. The Duffey Dome Formation underlies the metasedimentary unit of the Horseshoe Bend Formation at the headwaters of Marble Creek, Pulga quadrangle (Hietanen, 1973a), and thus seems to have the same stratigraphic position as the metabasalt in the vicinity of Brush Creek and Shute Mountain.

The quartzite of the Horseshoe Bend Formation is white to light gray, granular, and contains muscovite and biotite in varying amounts. Most of it is thin bedded with micaceous laminae and thin (½–1 cm thick) layers of phyllite. The beds in the gray quartzite are 1–10 cm thick and in the white quartzite 10–50 cm thick. There is every gradation from quartzite to phyllite and to micaceous layers with albite. Some pebbly layers and conglomerate are interbedded south of Little Marble Cone, west and northeast of Sky High, at Milsap Bar and on Fields Ridge. The pebbles are quartzite, more rarely metarhyolite or aplite. Some of the rocks mapped as quartzite are thin-bedded metachert, some metamorphosed weathered rhyolitic tuff.

Phyllite is fine grained and dark gray, rarely black. It consists of quartz, biotite, muscovite, some epidote, albite, magnetite, and hematite. Small crystals of tourmaline occur in some layers. Numerous small crystals of red garnet occur in quartz-rich phyllite south of Little Marble Cone; elsewhere garnet is rare. Calcareous layers are common in the phyllite near marble layers. Beds with lenses of white marble and others with abundant actinolite and epidote are interbedded in several localities south of the Hartman Bar pluton. A part of the epidote in these calcareous layers is segregaged into small lenses, (3 by 5 cm in size) and pyrite is a common accessory mineral. Disseminated carbon makes some layers black. Marble lenses in the black phyllite exposed in the streambed of the South Branch of the Middle Fork of the Feather River 1½ km northeast of Morgan Bar are 1–20 cm long and consist of either medium-grained calcite or calcite and quartz. In some of the small lenses, calcite and quartz grains have a spiral arrangement, giving an impression that they were fossils, but complete recrystallization makes further identification impossible. Thin sections show a granoblastic mixture of calcite and quartz devoid of all organic textures.

Pebbly layers are interbedded with phyllite that extends southeast from the vicinity of Maynards Ranch. East of the mouth of Lost Creek, this unit consists of dark-gray metagraywacke in which subangular to elongate clasts, 1–20 mm long, are metachert, quartzite, phyllite, and some metavolcanic rocks. Small fragments of quartz and occasionally albite are common in the matrix which consists mainly of micaceous minerals, quartz, and albite and is heavily dusted by carbonaceous material and iron oxides. Interbedded are tuffaceous layers with clasts of metavolcanic rocks in a matrix that contains chlorite, amphibole, epidote, and disseminated iron oxides.

Fine-pebble conglomerate and associated lithic metagraywacke that are somewhat less deformed than the other rocks of the Horseshoe Bend Formation are exposed 1–3 km south of Clipper Mills between Oroleve and Empire Ridge. Outcrops along a logging road 1 km south of Clipper Mills show a poorly developed foliation parallel to the regional trends. Boulders of very hard fine-pebble conglomerate farther south show a well-developed parallel orientation of subangular elongate clasts, in which relict structures and textures of Paleozoic source rocks are preserved. Two-thirds of the clasts consist of metachert and quartzite; the remaining one-third consists of phyllite, metavolcanic rocks, and marble. These clasts are similar to the rocks that make up the Calaveras Formation in the Bucks Lake quadrangle (Hietanen, 1973), about 30 km to the north and northeast. Only a few clasts consist of individual grains of quartz, hornblende, and plagioclase. The metavolcanic clasts consists of hornblende, biotite, epidote, albite, quartz, magnetite, and sphene altered to leucoxene. Hornblende, biotite, quartz, epidote can be identified in the matrix, which is heavily clouded with iron oxide. The similarity in the minenralogy of the volcanic clasts and the matrix suggests that the matrix contains tuffaceous material.

A similar lithic metagraywacke with an interbedded pebbly layer is exposed on the east side of the North Yuba River, east of the plutonic mass along the river. A fault separates the graywacke from the fine-grained phyllite to the east. Because of the closeness of the pluton, the graywacke here is strongly deformed and recrystallized.

Marble in the northern part of the area is distinctly bedded; thick (10–50 cm) coarse-grained layers of white calcite alternate with thinner light-gray layers that contain some muscovite, biotite, magnetite, and pyrite, and others that contain actionolite and epidote. Chemical analyses of marble near Milsap Bar (Hietanen, 1951, table 2) show that carbonate is calcite containing 0.8 percent MgO. Much of the marble in the canyon of the North Yuba River in the southern part of the map area has a lenticular structure. Lenses of coarse-grained white marble ranging from a few centimetres to several metres in length are embedded in dark amphibolite-rich matrix.

Metabasalt is dark greenish gray to black and generally well foliated. It was earlier called amphibolite (Hietanen, 1951), but relict textures, such as volcanic breccia and phenocrysts, prove its volcanic origin. Metabasalt consists of bluish-green hornblende, plagioclase, epidote minerals, and some quartz and biotite or chlorite. Accessory minerals are magnetite, sphene, leucoxene, and hematite. Plagioclase phenocrysts are common and usually include small crystals of hornblende. Phenocrysts of hornblende and aggregates of feltlike hornblende (presumably pseudomorphs after augite) occur in places. Vesicles are filled with calcite or epidote.

Layers of metatuff associated with metabasalt are thin bedded, dark to medium gray, and consist of hornblende, plagioclase, quartz, epidote, and magnetite. Near the plutons these layers are recrystallized to medium-grained hornblende gneiss. Thin layers of quartzite and phyllite are interbedded.

Meta-andesite and metadacite are similar to the corresponding rock types just north of the area in the Bucks Lake and Pulga quadrangles (Hietanen, 1973a, 1974); all consist mainly of hornblende, actinolite, epidote minerals, albite, and quartz, in varying proportions.

A few thin discontinuous layers of metarhyolite are interbedded with metabasalt and metasedimentary rocks west of the Cascade pluton. These are light gray to white, rich in quartz and feldspar, and contain less than 15 percent biotite plus muscovite; some hornblende and epidote are common. Difference in the potassium feldspar content indicates that there are two types of metarhyolite: The occurrences around the Horseshoe Bend at the northern boundary of the area of plate 1 contain very little or no potassium feldspar, whereas in the lenses west of Brush Creek, potassium feldspar content is 10–15 percent by volume.

Metarhyolite that contains numerous thin hexagonal plates of biotite oriented parallel to a gneissoid texture (fig. 3) was described and illustrated earlier (Hietanen, 1951) from a locality about 1 km northeast of Mountain House, in the southeastern border zone of the Merrimac pluton. Since the earlier fieldwork, other

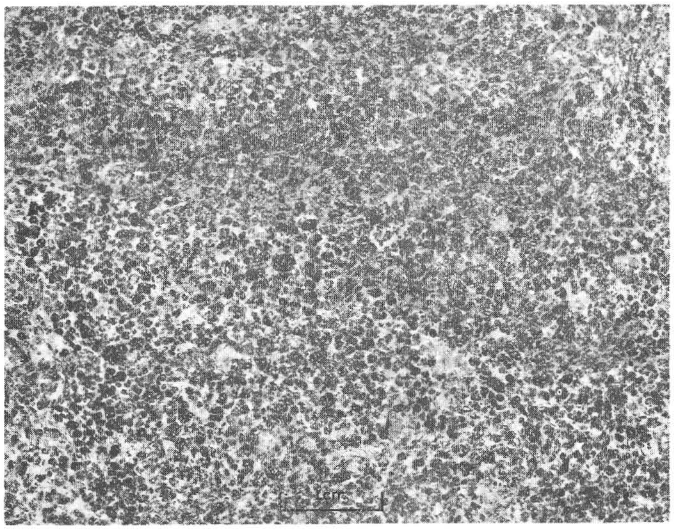

FIGURE 3.—Hexagonal plates of biotite (black) in metarhyolite north of Mountain House, southeastern contact zone of the Merrimac pluton (loc. 1470).

lens-shaped bodies of this unusual rock have been exposed in new roadcuts. Most of these are elongate inclusions in the quartz dioritic border zone of the Merrimac pluton; some metarhyolite is interlayered with phyllite and biotite quartzite that borders the pluton in this vicinity. The hexagonal biotite plates, 1–2 mm long and 0.1 mm thick, are embedded in a fine-grained groundmass that consists of albite, quartz, orthoclase, and muscovite. Biotite phenocrysts make up about 20 percent of this rock; quartz and albite phenocrysts are sparse. All phenocrysts are undeformed and are bounded by smooth euhedral crystal faces; in this, they contrast with the common deformed shape and in part sutured boundaries of the phenocrysts in the other metarhyolites of this formation. The biotite-rich metarhyolite is exceptionally well preserved or is perhaps younger, as similar undeformed textures are typical of Mesozoic metavolcanic rocks southwest of the area. (See section "*Age and Correlation*.")

A mesonorm in molecular percentages was calculated from the chemical analyses published earlier (Hietanen, 1951, table 1, analysis 406). It shows 25.9 quartz, 36.3 albite, 1.9 anorthite, 8.7 orthoclase, 11.5 muscovite, 14.4 biotite, 1.2 sphene, 0.2 apatite, and 0.1 magnetite, and it reflects the true mineral content of this rock, except that the actual percentage of biotite is higher (about 21) and that of muscovite lower (5), and that all iron and titanium are in biotite. The percentage of biotite is much higher than in normal rhyolites; that of orthoclase, lower. The euhedral biotite phenocrysts must have crystallized early in the magma, which was rich in iron (3.9 weight percent FeO) and contained more magnesium (1.6 percent MgO) and water than present in normal rhyolitic magma. The Mg/Fe ratio of biotite on the basis of rock analysis is

0.74, and its Al_2O_3 content about 17 percent.

Small occurrences of metarhyolite rich in biotite elsewhere in the Horseshoe Bend Formation (as a small outcrop in loc. 1570) have textures typical of common metarhyolite. Biotite is in small flakes or in thin laminae parallel to the foliation. Phenocrysts of albite and quartz have sutured borders, and many are granulated or deformed.

STRUCTURES

In the Franklin Canyon Formation, bedding is distinct and well preserved only in the tuffaceous and sedimentary layers (fig. 4). Pillow structures are well exposed on high vertical walls of a rock quarry at the south end of the Little Grass Valley Dam and along Slate Creek in the southeastern part of the area. The shape of the pillows indicates that the formation is right side up at these localities. Elsewhere, distribution of the rock types brings out a discontinuous layering and shows that all rocks are folded. In the north, folds are tight and isoclinal; toward the southeast, they become increasingly gentle, and in the eastern part of the mapped area (pl. 1), an S-shaped curvature is evident in the metatuff and interbedded black phyllite exposed along Slate Creek and vicinity. A roadcut between Slate Creek and Poverty Hill (fig. 5) exposes a recumbent fold on a southeast-plunging axis overturned to the southwest.

Lineation is well developed in the tuffaceous and sedimentary layers but absent in the massive parts of the flows. In the tuffaceous layers, lapilli are stretched parallel to it; in the sedimentary layers, it is an intersection of bedding and foliation. It plunges 25°–60° to the south-southeast. Where folds are exposed, their axes coincide with this lineation, which is thus a *b* lineation.

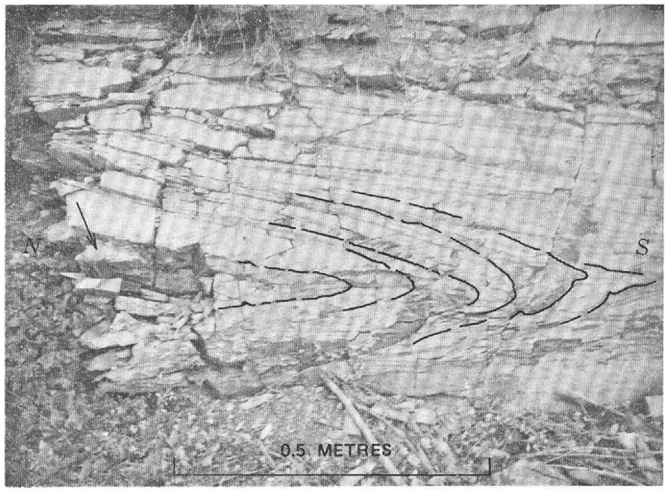

FIGURE 5.—Recumbent fold on southeast-plunging axis, indicating overturning to the southwest, in black phyllite at 4,200-foot elevation east of Slate Creek.

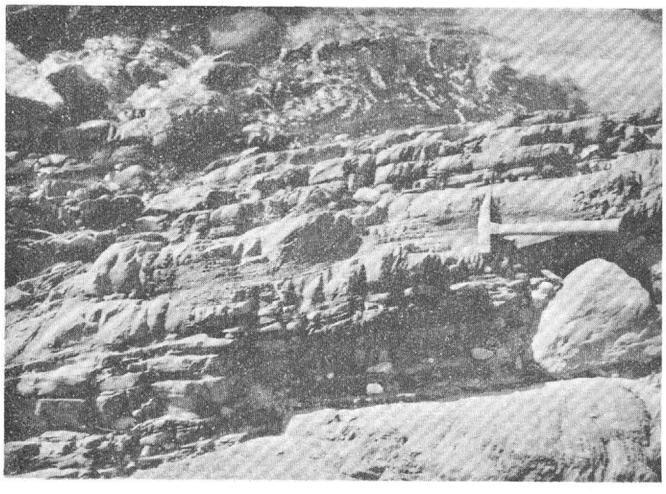

FIGURE 4.—Flat-lying bedding and poorly developed steep second cleavage in black Phyllite on Slate Creek, eastern part of the mapped area (pl. 1).

Foliation is marked in the metatuff and phyllite where micaceous minerals and amphiboles are parallel or subparallel to it. The massive parts of the flows are in general surrounded by foliated rock in which deformed blocks of massive lava are included. Foliation can be measured in most outcrops. In the metatuff and phyllite, it is parallel to the axial planes of folds and generally makes an angle with the bedding planes. In summary, the structures indicate that the Franklin Canyon Formation is isoclinally folded and has a well-developed axial plane foliation and a *b* lineation. Overturning to the west is common.

A second lineation, presumably an *a* lineation, was observed in only a few outcrops, as on Slate Creek in the eastern part of the area. The outcrops of metatuff and phyllite along Slate Creek show a second cleavage that strikes about N. 20° W. and is mostly vertical (fig. 4). This cleavage is a set of closely spaced fractures resembling slaty cleavage. There is no mineral orientation parallel to it, and it must therefore be later than the foliation. It is most likely related to the faulting.

Structures of the Horseshoe Bend Formation differ in many respects from those of the Franklin Canyon Formation, owing in part to the material folded and in part to deformation by emplacement of nearby plutons. Bedding is prominent in most rock types of this formation. In the quartzite and phyllite, thin beds, 1–5 cm thick, rich in either quartz or micas alternate or are separated by mica laminae. Individual beds in the marble (2–100 cm thick) are separated by thin dark-colored layers that contain some mica, magnetite, and pyrite. Thin (1–20 cm thick) phyllitic layers are interbedded in many places. Rocks mapped as metabasalt may include tuffaceous layers and some thin layers of quartzite and phyllite. In metatuff, beds are a few millimetres to about 20 cm thick, rarely thicker. The meta-andesite and metadacite that occur in rather thin layers and lenses in the northern and southwestern parts of the area include some tuffaceous layers that yielded during the deformation but left the flows undeformed.

Two sets of folds and two lineations are apparent in the metamorphic rocks near the plutons. The trend of the major axis deviates from its regular northwesterly direction around the plutons, having been modified by them. The plunge of the major axis is commonly to the east or to the southeast. The folds on this axis are tight and isoclinal, and the rock masses are elongate parallel to it.

A second set of folds have axes parallel to the lineation that plunges to the northeast or nearly so, about at right angles to the major fold axes. This lineation, an *a* lineation in relation to the major folds, is strongest around the northwestern end of the Cascade pluton, where thin-bedded phyllite has small folds around it. Large folds around the *a* lineation are evident in the rocks between the Cascade and Merrimac plutons. It seems reasonable to assume that this folding and lineation are later than the major folding and were formed during the emplacement of the plutons. Compton (1955, pl. 1) mapped a similar lineation in the border zone of the Bald Rock pluton and in its metamorphic wall rocks south of Brush Creek. The parallelism of the lineation in the pluton and its wallrocks certainly proves a common origin. This second lineation, prominent in the Horseshoe Bend Formation but negligible in the Franklin Canyon Formation, is a later feature than the major northwest trends.

AGE AND CORRELATION

The metavolcanic and metasedimentary rocks can be tentatively correlated with units in nearby areas on the basis of lithology and continuation of major structures. The southward continuations of the Franklin Canyon and Horseshoe Bend Formations are shown as Paleozoic metavolcanic and metasedimentary rocks on the geologic map of California, Chico sheet (Burnett and Jennings, 1962). The metabasalt around the southern panhandle of the Lumpkin pluton is shown as Mesozoic on that map. Detailed mapping for this study, however, suggests that this metabasalt is a part of the Horseshoe Bend Formation. Interbedded layers of quartzite, metatuff, and metarhyolite, similar to those in the Horseshoe Bend and its northward extension of andesitic metabasalt, underlie the quartzite of the Horseshoe Bend Formation east of Sugar Pine Point at the south end of Lumpkin Ridge.

It was earlier pointed out (Hietanen, 1973a) that the succession of pyroclastic and sedimentary units of the Franklin Canyon and Horseshoe Bend Formations is broadly similar to the Devonian and Permian in the Taylorsville area as given by McMath (1966). Correlation of the tectonic elements of the northern Sierra Nevada and the Klamath Mountains (Davis, 1969; Irwin, 1966) suggests that deposition of the rock units west of the Melones fault may have been roughly contemporaneous with units west of the Trinity fault in the Klamath Mountains. Specifically, the Franklin Canyon Formation could be correlative with Devonian pyroclastic rocks in the Klamath Mountains, and limestones of the Horseshoe Bend Formation could be correlative with the lenses of coarsely crystalline Permian limestone in the Paleozoic sequence in the Klamath Mountains. A Permian(?) age was assigned by Creely (1965) to similar limestone west of the study area.

The Franklin Canyon Formation that underlies the Horseshoe Bend Formation in the Pulga quadrangle (Hietanen, 1973a) consists of a metamorphosed potassium-poor pyroclastic andesite-sodarhyolite sequence typical of island arcs. These rocks overlie the metachert and interbedded phyllite mapped as the Calaveras Formation in the adjoining Bucks Lake quadrangle (Hietanen, 1973a). All these rocks are exposed just west of a serpentine belt along the Melones fault and together form a sequence that is common on the ocean floors. This stratigraphy supports the contention of Burchfiel and Davis (1972) that in Devonian time an island-arc system extended from the Klamath Mountains to the northern Sierra Nevada. In contrast to the potassium-poor andesite and sodarhyolite in the Devonian(?) Franklin Canyon Formation, the volcanogenic rocks in the Permian(?) Horseshoe Bend Formation are basalt and in part potassium-rich rhyolite, and the interbedded metasediments include shallow-water limestones. These changes in composition resulted from changes in conditions of formation of magmas and of deposition in a tectonically active belt. (Discussed under "Origin of Magmas.")

Comparison of the structures and textures of the Franklin Canyon Formation with petrologically similar but much less deformed Mesozoic metavolcanic rocks southwest of the Big Bend fault (fig. 2) supports the suggestion of a Paleozoic age for the Franklin Canyon Formation. The metavolcanic rocks southwest of the Big Bend fault form the northern end of the westernmost metamorphic belt of the Sierra Nevada. The metavolcanic rocks of this belt are generally considered Jurassic in age (Taliaferro, 1943; Clark, 1964, Bateman and Wahrhaftig, 1966).

The Mesozoic metavolcanic rocks southwest of the Big Ben fault are well exposed along the North Fork of the Feather River east of Las Plumas. A brief description and chemical analyses of the major rock types in this section were included in the Merrimac report (Hietanen, 1951). These rocks belong to a calc-alkaline andesitic suite poor in potassium. The major rock types are meta-andesite and metadacite with interbedded layers of metatuff. Metamorphosed sodarhyolite and basaltic andesite are intercalated with metadacite in the eastern part of the section. Petrologically these rocks are similar to the Franklin Canyon Formation, but there are certain distinct structual, textural, and chemical differences.

The most notable differences between these two andesitic suites are in structures and textures of meta-andesite, metadacite, and metamorphosed sodarhyolite. In the Franklin Canyon Formation, all rocks are generally strongly deformed, and recrystallization has modified or obliterated the original textures. The volcanic bombs and pillows are flattened parallel to the foliation and stretched parallel to the lineation. The phenocrysts have partly sutured boundaries and contain mineral inclusions, such as chlorite and amphiboles in plagioclase, which indicate migration of ions during the metamorphism. In contrast the Mesozoic rocks are either undeformed or show only a weak foliation. The primary structures and textures such as volcanic bombs and phenocrysts have preserved their original shape or are only slightly elongate parallel to the regional trends (see Hietanen, 1951, fig. 3; fig. 1, pl. 2 and fig. 1, pl. 3). Phenocrysts are bounded by well-developed smooth crystal faces, and their inclusions are products of isochemical recrystallization (save addition of H_2O) such as epidote after anorthite component of plagioclase and muscovite after orthoclase originally contained in the plagioclase phenocrysts.

Comparison of the chemical composition of the corresponding members of these two andesitic suites shows that the rocks of the Franklin Canyon Formation (Hietanen, 1973a, table 1, analyses 463, 464, 461) contain less SiO_2 and alkalies and more CaO and MgO than their less altered Mesozoic counterparts (Hietanen, 1951, table 1, analyses 2, 3, 4, 6). This is in agreement with the trend of migration of material in the Paleozoic formations during their regional metamorphism. It was suggested in an earlier paper (Hietanen, 1973b) that the metamorphic rocks above a plutonic magma chamber were bled of elements (mostly Si, K, Na) needed for the formation of monzotonalitic magmas by differential melting and were enriched in residual elements (Ca, Fe, Mg). These chemical changes are reflected in the quantitative mineralogy of the rock units of the Franklin Canyon Formation.

The metavolcanic rocks bordering the Bald Rock pluton around its southeast corner are probably correlative with rocks shown as Mesozoic metavolcanic rocks on the geologic map of California, Chico sheet (Burnett and Jennings, 1962). Field observations on Sucker Run, on a small dirt road north of the South Fork of the Feather River, and on the Old Forbestown Road south of this river suggest that these Mesozoic(?) metavolcanic rocks are separated by a north-trending fault from the metasedimentary rocks of the Horseshoe Bend Formation in the east. Metabasalt, metadacite, and metarhyolite were identified on the west side of the fault. Metadacite has long slender laths of plagioclase and clusters of epidote embedded in a fine-grained groundmass consisting of quartz, feldspar, chlorite, muscovite, and some epidote and biotite. Ilmenite, partly altered to leucoxene, is a common accessory mineral in this rock.

The fine-pebble conglomerate and associated metagraywacke south and southeast of Clipper Mills is younger than the Paleozoic formations (Calaveras?) from which the clasts were derived. These early Paleozoic rocks had undergone deformation and recrystallization before they were broken up and the fragments transported into a basin that also received some tuffaceous material from erupting volcanoes nearby. The distance of transportation was short enough to preserve the subangular shapes of many clasts but long enough to allow considerable sorting according to the pebble size (fig. 6). The deposition of this graywacke was after a Paleozoic deformation and recrystallization but before the Jurassic (Nevadan) orogeny and before the Mesozoic volcanism.

METAMORPHOSED INTRUSIVE ROCKS

The most mafic among the regionally metamorphosed synkinematic intrusive rocks are the peridotites and pyroxenites that occur mainly as long thin

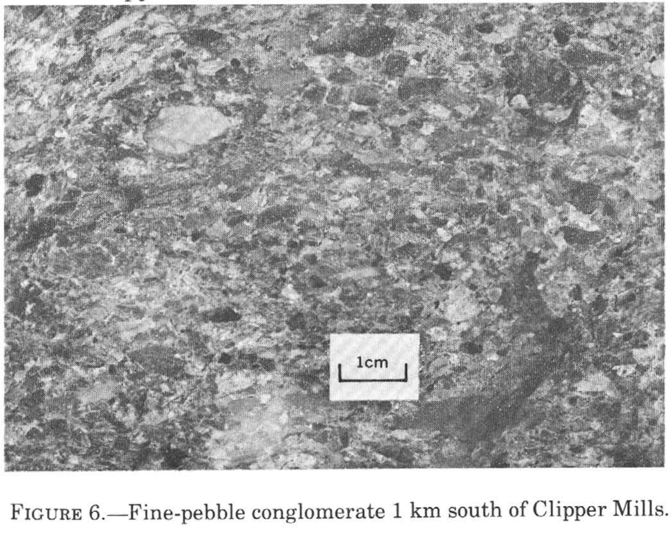

FIGURE 6.—Fine-pebble conglomerate 1 km south of Clipper Mills.

bodies along the fault zones and are partly altered to serpentine, soapstone, and talc schist. Metagabbro, metadiorite, and metatrondhjemite in small bodies elongate parallel to the structural trends represent intrusive equivalents of the metavolcanic rocks they intrude and with which they were deformed and recrystallized. It has been shown (Hietanen, 1973a) that in chemical composition and trace-element content, the synkinematic intrusive rocks are similar to the metavolcanic series but different from the postkinematic Late Jurassic and Early Cretaceous plutons. The medium-grained equigranular texture of the synkinematic intrusive rocks suggests emplacement at shallow depths.

SERPENTINE AND PERIDOTITE

Numerous elongate bodies of peridotite at various stages of alteration to serpentine, soapstone, and talc schist are enclosed in the metamorphic rocks, mainly along the fault zones. The Camel Peak fault is accompanied by these ultramafic rocks for all of its exposed length (fig. 2; pl. 1). Most of the thick bodies consist of peridotite that is altered to serpentine minerals only along tiny cracks and fractures. The border zones of these bodies consist of serpentine, soapstone, and talc schist, the alterations being similar to those of ultramafic rocks described in the Bucks Lake quadrangle (Hietanen, 1973a). A layer of talc-tremolite rock is common along the contacts.

The peridotite is dark greenish gray and fine grained. It consists of anhedral grains of olivine 0.02–0.03 mm in diameter, prisms of enstatite and augite 0.1–0.2 mm long, grains of magnetite, and some serpentine minerals along tiny fractures. Colorless hornblende rich in magnesium (Hietanen, 1973a) is a primary mineral in some of the peridotite. Parts of the bodies are sheared and completely altered to serpentine and soapstone.

METAGABBRO

A large inhomogeneous body of metagabbro is exposed along Slate Creek just east of the serpentine that accompanies the Camel Peak fault. Three somewhat smaller (3–4 km long) bodies lie between the Cascade pluton and Lumpkin pluton. A fairly large mass is in the southeastern corner of the area, but elsewhere only a few small bodies occur next to serpentine and metadiorite. The largest body is well exposed along Slate Creek below the dam, which is 200 metres north of the southern border of Plumas County. The metagabbro is a dark coarse- to medium-grained slightly foliated rock in which hornblende and plagioclase can be identified in the hand specimen. In thin sections the hornblende is blue green and strongly pleochroic (γ = blue green, β = green, α = very pale green) and in places forms clusters of small prisms. Plagioclase (An_{35}) contains abundant small inclusions of quartz, epidote, and hornblende or consists of a mixture, mainly epidote with less albite. Quartz, actinolite, and clinozoisite occur in varying amounts. The common accessory minerals are magnetite, ilmenite, and rutile. The variable ratios of the major constituents give rise to a considerable inhomogeneity within the masses. Brecciated metagabbro at the west end of the bridge over Slate Creek, 150 metres north of the southern boundary of Plumas County, consists of angular fragments of fine-grained dark metagabbro and interstitial light-colored material consisting of plagioclase, epidote, and quartz with chlorite and some hornblende.

METADIORITE

The largest mass of metadiorite lies just east of thin masses of metagabbro and serpentine that accompany the Camel Peak fault. Most of the other masses intrude the Franklin Canyon Formation. Metadiorite is a medium-grained hornblende-plagioclase-epidote-quartz rock that shows a crude foliation. Hornblende is the chief dark mineral, constituting about 30 percent of the rock. It is blue-green and strongly pleochroic near the postkinematic plutons but pale green elsewhere. Actinolite occurs in tiny prisms in plagioclase and forms the ends of some green hornblende prisms. Plagioclase is albitic in masses far from the plutons, rich in anorthite near the plutons. Epidote minerals, clinozoisite and epidote, more rarely zoisite, constitute about 30 percent of the metadiorite outside 1–2 km wide contact zone of the plutons. Most metadiorite contains about 10 percent quartz, some leucoxene, magnetite, and pyrite.

METATRONDHJEMITE

Several elongate conformable bodies of metatrondhjemite occur in the eastern part of the area. In outcrop these rocks resemble metadiorite except that they contain less hornblende and more quartz. They are medium grained, light bluish gray, and slightly foliated. They contain about 60 percent albitic plagioclase and 25–30 percent quartz. Potassium feldspar is absent. Dark constituents are either chlorite and epidote, or green hornblende, actinolite, biotite, and epidote. Muscovite occurs in places. Rutile, leucoxene, and magnetite are the common accessory minerals. Albitic plagioclase includes numerous small grains of epidote and some sericite. As hornblende increases and quartz decreases, these rocks grade through metatonalite to metadiorite. The texture is granoblastic, with large anhedral to subhedral grains of plagioclase and interstitial aggregates of small strained quartz grains that have interlocking boundaries. These aggregates were originally individual large grains of quartz that were granulated during deformation.

The mineral content, and presumably the chemical composition, of metatrondhjemite is similar to that of the metamorphosed sodarhyolite. The coarse grain size and equigranular texture indicate deep-seated cooling of the trondhjemitic magma. The metatrondhjemite is thus a deep-seated equivalent of the metasodarhyolite, a relation similar to that described earlier between meta-andesite and metagabbro and between metadacite and metadiorite in the Bucks Lake quadrangle (Hietanen, 1973a).

METAMORPHISM

Metamorphism has equally affected the metavolcanic, metasedimentary, and the oldest intrusive rocks. All these rocks were recrystallized to the borderline of the greenschist and epidote-amphibolite facies during a regional metamorphism that accompanied the folding on the major northwest axes. A second (contact) metamorphism affected rocks in about a mile wide zone around the Jurrassic and Cretaceous plutons. In this zone, higher grade minerals such as staurolite, cordierite, and andalusite crystallized in the pelitic layers, and blue-green aluminum-rich hornblende, clinozoisite, and epidote crystallized in the metavolcanic rocks, indicating pressure-temperature conditions near the borderline of the epidote-amphibolite and amphibolite facies. The relation between the deformation, recrystallization, and plutonism is similar to that described from the area farther north (Hietanen, 1973a).

The Franklin Canyon Formation is not exposed near the plutons, and its recrystallized mineral assemblages are those typical of the low grade metamorphism. Primary minerals such as augite and hornblende are rarely preserved. The outline of pseudomorphs allow the identification of the original phenocrysts and together with the bulk composition serve to identify the original rock types. The typical mineral assemblage is epidote-clinozoisite-albite-actinolite-green hornblende-chlorite with or without quartz. Biotite and muscovite with some garnet occur in the interbedded pelitic layers. These mineral assemblages indicate recrystallization at temperatures and pressures near the borderline of the greenschist and epidote-amphibolite facies.

The Horseshoe Bend Formation envelopes the Jurassic and Cretaceous plutons and sustained a higher grade metamorphism and stronger deformation than the Franklin Canyon Formation. The most common amphibole in the metavolcanic rocks is a blue-green variety that in the Bucks Lake quadrangle occurs in the highest grade zone near the plutons and was found to be rich in aluminum and sodium (Hietanen, 1974). Most phyllite contains biotite but no chlorite; garnet occurs in only a few localities. Metatuff next to the Bald Rock pluton recrystallized as hornblende gneiss with a grain size coarser than that present in metatuff farther from the contact. Metabasalt and associated metatuff between the Merrimac and Bald Rock plutons were recrystallized as amphibolite and hornblende gneiss. A small lens of interbedded calcareous sediment (loc. 1519) recrystallized as coarse-grained grossularite-diopside-epidote-plagioclase (An_{33})-quartz rock with some zoisite, clinozoisite, and sphene. Similar contact rocks are common in calcareous layers in the Pulga quadrangle, where the mineral assemblages in the interbedded pelitic layers (staurolite-andalusite-biotite-quartz in the outer and andalusite-cordierite-biotite-quartz in the inner contact aureole) indicate metamorphism at the lower border of the amphibolite facies (Hietanen, 1967, 1973a).

PLUTONIC ROCKS

A sequence of postkinematic plutonic rocks, determined on the basis of field relations, structures, textures, mineralogy, and composition, comprises three groups: earliest postkinematic intrusions, the main mass of the Cascade pluton and the Hartman Bar pluton, and trondhjemite. (1) The earliest postkinematic intrusions include an altered gabbro on Swain Hill and vicinity and related dioritic masses, the Lumpkin pluton, and a small mass of quartz diorite at Frey Creek. The westernmost marginal mass of the Cascade pluton resembles the quartz diorite at Frey Creek in its mineralogy and texture and may have been intruded during the same episode. (2) The main mass of the composite Cascade pluton was emplaced later than the westernmost marginal mass. The main mass grades from foliated quartz diorite along the borders to massive monzotonalite in the southeastern interior. The Hartman Bar pluton is texturally and mineralogically similar to the main part of the Cascade pluton and presumably is comagmatic and was emplaced during the same episode. (3) A trondhjemitic tongue extends eastward from the northern part of the Bald Rock pluton and cuts discordantly the metamorphic wall-rocks between the two plutons and the western part of the Cascade pluton. The trondhjemite was therefore emplaced after the Cascade pluton had solidified. Each of the three groups has characteristic textural and mineralogic features that help in correlating these rocks with the plutonic rocks farther north, where the Bucks Lake, Grizzly, and Merrimac plutons were dated by Grommé, Merrill, and Verhoogen (1967) at 142 (Late Jurassic) to 128 (Early Cretaceous) million years.

LUMPKIN PLUTON AND RELATED ROCKS

A large body of altered gabbro exposed around Swain Hill northwest of Feather Falls was briefly described by Compton (1955) in connection with his study of similar rocks—considered Late Jurassic by him—south of the Bald Rock pluton. Two small dioritic plutons, the Lumpkin pluton and the quartz diorite at Frey Creek, are partly surrounded by the altered gabbro on Swain Hill. The total area covered by these altered plutonic rocks is about 28 square kilometres. Several small masses of altered quartz diorite occur south of Lumpkin pluton. The texture of all these rocks is hypidiomorphic, with subhedral plagioclase and hornblende. As is common in the postkinematic plutons, only the border zones are foliated; in the centers, minerals are randomly oriented. These rocks, however, are partially recrystallized, as shown by abundant epidote, granulated quartz, and small prisms of bluish-green hornblende included in plagioclase. This partial recrystallization, due to reheating during the emplacement of younger plutons, was accompanied by addition of water. An outcrop of pyroxene gabbro that resembles the pyroxene diorite in the center of the Bucks Lake pluton, except for more pyroxenes in the gabbro, is exposed in a roadcut north of Swain Hill (loc. 1337, pl. 1). Because of their partial recrystallization, all these rocks are considered to be older than the large plutons but considerably younger than the deformed and regionally metamorphosed synkinematic intrusive rocks.

The pyroxene gabbro north of Swain Hill consists of ortho- and clinopyroxene, hornblende, plagioclase (An_{70}), and some olivine, quartz, magnetite, and sphene. The texture is granoblastic, with rounded pyroxene grains. A few poikilitic hornblende crystals include round grains of pyroxene and plagioclase. Large pyroxene grains include rounded olivine grains, some partly altered to a mixture of chlorite, serpentine, and magnetite. Olivine that is not included in pyroxene and some large poikilitic magnetite grains have a narrow corona of green hornblende. Symplectic intergrowth of orthopyroxene and magnetite in the centers of some pyroxene crystals may indicate former olivine. Plagioclase (An_{70}) is in stubby subhedral crystals that are ½–1½ mm long and show polysynthetic twinning.

Hornblende gabbro is very dark gray to black, fine to medium grained, and consists mainly of hornblende and plagioclase. On Swain Hill green hornblende is rimmed by blue-green hornblende; similar hornblende occurs also as individual homogeneous crystals of various sizes. The centers of large grains and aggregates of green hornblende have inclusions of small round grains of quartz. In the Bucks Lake quadrangle, this texture was traced to pyroxene that had been altered to hornblende during a later phase of intrusion (Hietanen, 1973a). In hornblende gabbro near the Bald Rock pluton, all hornblende is intensely blue green. Some of the grains are large holoblasts that include quartz, plagioclase, epidote, magnetite, and numberous tiny grains of magnetite and scales of ilmenite.

In most hornblende gabbro, plagioclase is An_{52-65}; near the Bald Rock pluton, it is An_{40} and is accompanied by many large grains of epidote and many tiny inclusions of quartz. Plagioclase grains are either subhedral or anhedral and irregular in outline. Complex twinning is common. Small flakes of biotite, some quartz and alteration products, epidote and chlorite are more abundant along the border zones than in the central part. Apatite in small euhedral crystals, magnetite, ilmenite, and sphene are the accessory minerals.

The quartz diorite on Frey Creek is coarse- to medium-grained hornblende-plagioclase rock with a hypidiomorphic slightly foliated texture. Plagioclase (An_{36-37}) constitutes about 55 percent of this rock, hornblende 20–30 percent, quartz 10–20 percent, and biotite about 1 percent. The mineral content measured in two stained specimens is shown in table 1, and the chemical analysis of one of these (sample 1267) is shown in table 2. Magnetite and sphene are common accessory minerals; chlorite, epidote, and muscovite occur as alteration products. Plagioclase includes grains of epidote; the centers of some large zoned crystals are altered to a mixture of epidote and muscovite. Hornblende includes small grains of quartz and magnetite and is pleochroic: γ=blue green, β=green, α=light green. The blue-green color is typical of the recrystallized hornblende of this rock and contrasts with the olive-green color of the igneous amphiboles in the younger plutonic rocks.

The Lumpkin pluton, at its northernmost border zone, consists of coarse-grained hornblende gabbro that grades into a dioritic rock toward the south. This gabbro is mineralogically and texturally similar to the dioritic main mass, except for a higher percentage of hornblende. It represents a marginal accumulation of early crystallized dark constituents. In places the contact between this gabbro and the older enveloping one is obscure. The main part of this pluton consists of brownish-gray medium-grained diorite in which the major constituents—plagioclase (An_{27-35}), epidote, hornblende, chlorite, and quartz—occur in varying proportions (table 1, locs. 1531, 1532). Most plagioclase grains have been altered to epidote with only a small amount of twinned oligoclase. Chlorite is a common alteration product after biotite and hornblende. Hornblende is bluish green to green and occurs in large subhedral crystals. Magnetite and apatite are the accessory minerals.

TABLE 1.—*Percentage of major constituents measured in stained samples of plutonic rocks*
[Analyst: M. B. Norman; M204 is from Hietanen (1951)]

Rock type	No.	Locality	Specific gravity	Plagioclase	Quartz	K-feldspar	Biotite and hornblende
Cascade Pluton							
Hornblende-biotite quartz diorite	1	1552	2.71	58.9	10.6	7.3	23.2
Do	2	1200	2.71	59.7	18.3	0	22.0
Do	3	1209	2.74	61.0	16.4	1.2	21.4
Do	4	1330	2.75	An$_{37}$ 58.5	20.1	0	21.4
Do	5	1308	2.74	An$_{36}$ 62.7	16.0	0	21.3
Do	6	1224	2.69	63.6	16.8	0	19.6
Do	7	1207	2.75	An$_{25-30}$ 60.4	17.2	3.6	18.8
Do	8	1206	2.76	An$_{30}$ 61.3	16.8	3.3	18.6
Do	9	1208	2.73	An$_{35}$ 66.4	13.6	2.0	18.0
Do	10	1328	2.58	63.3	18.1	0	18.6
Do	11	1309	2.76	An$_{36-37}$ 61.3	20.3	0	18.4
Tonalite	12	1211	2.71	61.1	20.3	1.5	17.1
Do	13	1248	2.75	An$_{36-43}$ 60.2	23.8	0	16.0
Do	14	1223	2.78	68.4	15.8	0	15.8
Do	15	1370	2.77	65.6	15.6	3.1	15.7
Do	16	1362	2.69	65.2	19.3	0	15.5
Monzotonalite	17	1555	2.68	61.6	15.2	7.8	15.4
Tonalite	18	1556	2.74	An$_{35-46}$ 61.7	23.2	.2	14.9
Do	19	1450	2.72	56.8	23.5	5.5	14.2
Do	20	1364	2.71	60.4	23.5	2.0	14.1
Do	21	1270	2.68	An$_{32}$ 59.3	27.0	.1	13.6
Monzotonalite	22	1271	2.70	An$_{20-30}$ 57.3	25.2	7.2	10.3
Tonalite	23	1272	2.69	An$_{28}$ 59.4	25.7	5.2	9.7
Do	24	1367	2.71	An$_{26-32}$ 60.0	25.5	5.7	8.8
Do	25	1368a	2.68	61.1	26.2	5.2	7.5
Trondhjemite	26	1368b	----	66.8	24.8	2.8	5.6
Trondhjemitic tongue in Cascade Pluton							
Trondhjemite	27	1205	2.70	An$_{17-24}$ 64.0	25.0	2.0	9.0
Do	28	1327	2.59	57.0	28.7	9.3	5.0
Do	29	1210	2.63	An$_{25}$ 56.7	30.8	8.2	4.3
Do	30	1313	2.65	An$_{14-32}$ 61.5	28.7	5.7	4.1
Do	31	1311	2.61	67.6	24.1	4.3	4.0
Do	32	1312	2.57	66.9	24.6	5.2	3.3
Do	33	649	2.62	62.1	25.8	8.7	3.4
Do	34	648	2.62	61.0	28.7	7.2	3.1
Bald Rock pluton							
Hornblende quartz diorite	35	1451	2.64	An$_{20-35}$ 49.3	22.1	6.9	21.7
Do	36	1326	2.64	53.1	21.2	5.6	20.1
Monzotonalite	37	1492	2.67	An$_{25-31}$ 50.0	27.5	9.4	13.1
Trondhjemite	38	1452	2.68	An$_{25}$ 54.6	36.9	2.3	6.2
Granite-trondhjemite	39	M204	----	An$_{17}$ 53.2	30.7	9.9	4.5
Trondhjemite	40	1461	2.64	61.6	29.1	5.6	3.7
Shute Mountain mass							
Trondhjemite	41	1462	2.53	61.6	29.5	0	8.9

Quartz diorite in small masses at Mount Hope and near Orleve in the southern part of the area resembles quartz diorite at Frey Creek in the outcrop but is somewhat finer grained and grades in places to a light-colored tonalite. Thin sections show that plagioclase is altered to a mixture of epidote and sericite that includes some small grains of hornblende and chlorite. The percentage of quartz is higher than in the Frey Creek mass, generally ranging from 15 to 30 percent.

CASCADE PLUTON

Two distinctly different phases of intrusion can be recognized in the composite Cascade pluton: a quartz diorite main mass that grades through tonalite to monzotonalite in the eastern part and a later trondhjemitic tongue that cuts the western part of the pluton. The western border zone near the mouth of the South Branch of the Middle Fork of the Feather River (secs. 1 and 2, T. 21 N., R. 6 E.) is probably somewhat older

TABLE 1.—*Percentage of major constituents measured in* [illegible]*d sam*[illegible]—Continued

Rock type	No.	Locality	Specific gravity	Plagioclase	Quartz	K-feldspar	Biotite and hornblende
Merrimac Pluton							
Diorite	42	1557	2.8[illegible]	An_{37-55} 68.2	6.0	0	25.9
Hornblende-biotite quartz diorite	43	1468	[illegible]	An_{30-40} 54.9	23.3	0	21.9
Do	44	1521	[illegible]	55.2	22.6	1.6	20.6
Do	45	1604	2.71	An_{23-45} 55.2	21.0	3.2	20.6
Do	46	1612	2.71	54.4	21.0	4.6	20.0
Do	47	1616	2.73	An_{30-37} 59.2	19.1	2.7	19.0
Do	48	1522	2.70	An_{32-36} 51.0	23.9	5.7	19.5
Do	49	1610	2.73	An_{20-38} 53.2	24.3	3.9	18.6
Do	50	1611	2.72	53.7	25.0	2.9	18.4
Do	51	1515	2.64	52.9	24.7	4.1	18.4
Monzotonalite	52	1606	2.71	52.3	22.8	7.7	17.2
Tonalite	53	1615	2.72	An_{24-36} 57.2	24.0	3.4	15.4
Do	54	1559	2.74	61.7	23.2	.2	14.9
Do	55	1608	2.67	53.1	29.6	3.7	13.6
Do	56	1613	2.70	An_{23-45} 55.9	25.3	5.3	13.5
Monzotonalite	57	1607	2.68	57.0	23.9	5.8	13.3
Tonalite	58	1614	2.68	An_{23-45} 58.1	26.7	5.6	9.6
Monzotonalite	59	1605	2.64	An_{22-47} 45.0	28.7	18.5	7.8
Hartman Bar Pluton							
Hornblende quartz diorite	60	1214	2.77	An_{38} 61.9	17.7	0	20.4
Tonalite	61	1281	2.75	57.9	31.5	0	10.6
Trondhjemite	62	1282	2.67	53.2	39.5	0	7.3
Do	63	1292	2.70	49.7	43.8	0	6.5
Lumpkin pluton							
Diorite	64	1531	2.98	48.2	11.1	----	40.7
Quartz diorite	65	1532	2.90	55.9	13.8	----	30.3
Frey Creek mass							
Hornblende quartz diorite	66	1267	0	An_{36-37} 56.0	14.0	0	30.0
Do	67	1333	2.77	An_{32} 60.3	20.3	0	19.4
Hampshire Creek mass							
Monzotonalite	68	1621	2.66	An_{28} 36.8	41.2	16.2	5.8
Indian Valley mass							
Tonalite	69	1910	2.72	An_{30} 57.0	23.3	4.7	15.0

than the border zone of the main mass. This western border zone, about 1–2 km wide, consists of altered quartz diorite that in many respects resembles the quartz diorite at Frey Creek. Moreover, it contains discontinuous thin layers of metamorphic rocks and dikelike bodies of intrusive rocks—hornblendite, gabbro, and trondhjemite. On the south slope of the Middle Fork (loc. 1206, pl. 1), a fault separates this altered quartz diorite from the normal border-zone type in the east. A similar altered quartz diorite is exposed for 100 metres in a roadcut about 700 metres to the southeast. This large inclusion is enclosed in the quartz diorite of the normal border zone, indicating that the older altered quartz diorite formerly occupied a wider area in this vicinity.

The main part of the Cascade pluton is zoned in an irregular manner. The border zones and the west-central part consist of hornblende-biotite quartz diorite that is devoid of potassium feldspar (see table 1; fig. 7); in the southeast-central part, this rock grades through a lighter colored tonalite to monzotonalite. A tongue of light-colored trondhjemite that extends from the Bald Rock pluton through the metamorphic wall-rocks and western border phase into the main mass of the Cascade pluton continues northward and forms the northwestern tip of the Cascade pluton. A sharp discordant contact between this youngest rock and the main mass is exposed in roadcuts on Watson Ridge.

The western border zone, believed to be somewhat older than the main mass, consists of well-foliated

TABLE 2.—*Chemical composition in weight and ionic percentages, molecular norm, and trace-element contents of plutonic rocks*
[Analysts: chemical analyses, Elaine Brandt; trace elements, Nancy Conklin]

Sample	1267		1367		1313	
Locality	Frey Creek		South Fork, Feather River			
Rock type	Hornblende quartz diorite		Biotite tonalite Cascade pluton		Trondhjemite Cascade pluton	
	Weight percent	Cation	Weight percent	Cation	Weight percent	Cation
SiO_2	58.28	56.46	66.76	62.26	72.62	67.42
TiO_2	.86	.62	.31	.22	.12	.08
$Al_2O_3(AlO_{3/2})$	17.86	20.40	17.06	18.75	15.72	17.20
$Fe_2O_3(FeO_{3/2})$	2.43	1.77	1.05	.74	.43	.30
FeO	4.80	3.89	1.93	1.51	.66	.51
MnO	.16	.13	.09	.07	.05	.04
MgO	2.35	3.40	1.29	1.79	.33	.46
CaO	6.60	6.85	4.57	4.57	2.70	2.69
$Na_2O(NaO_{1/2})$	2.92	5.49	4.40	7.96	5.25	9.45
$K_2O(KO_{1/2})$	.64	.79	1.70	2.02	1.49	1.76
$P_2O_5(PO_{5/2})$	.23	.19	.11	.09	.04	.03
CO_2	.01	.01	.03	.04	.04	.05
$H_2O+(OH)$	1.84	(11.89)	.48	(2.99)	.29	(1.80)
H_2O-	.78	------	.05	------	.03	------
Total	99.76	100.00	99.83	100.00	99.77	100.00
Total anions	------	171.26	------	168.89	------	171.65
Molecular norm						
Q	18.66		20.77		27.84	
Co	1.08		.01		.82	
Or	3.95		10.11		8.82	
Ab	27.45		39.78		47.25	
An	32.60		21.92		12.92	
En	6.80		3.59		.91	
Fs	5.04		1.98		.64	
Mt	2.65		1.11		.45	
Il	1.24		.43		.17	
Ap	.51		.23		.08	
Cc	.02		.08		.10	
Total	100.00		100.00		100.00	
Trace elements, in parts per million						
Ba	250		780		720	
Co	13		5		0	
Cr	8		10		<5	
Cu	17		15		<2	
Ni	0		4		<4	
Sc	35		8		0	
Sr	190		570		500	
V	160		65		18	
Y	60		<20		<20	
Yb	5		<5		<5	
Zr	79		100		73	
Ga	17		15		14	

greenish-gray biotite-hornblende quartz diorite that contains 12–15 percent secondary minerals—epidote, muscovite, chlorite, and second-generation biotite and hornblende. Subhedral large grains (3–7 mm long) of plagioclase (An_{30}) are studded with small prisms of epidote and include scattered tiny flakes of green biotite, muscovite, and chlorite and small prisms of hornblende. These large altered plagioclase grains are embedded in a mosaic of tiny grains of quartz and plagioclase. Large grains of quartz (0.2–0.5 mm long) form monomineralic clusters that are strongly elongate parallel to the foliation. Biotite, hornblende, and the large grains of epidote are clustered subparallel to the foliation. The accessory minerals are magnetite, sphene, and apatite. Some of the large epidote grains are pleochroic in greenish yellow. Hornblende has pleochroism, γ=dark bluish green, β=green, α=pale green, the bluish tint being typical of the recrystallized hornblende in this area. These textural and mineralogic features indicate stronger deformation and more thorough recrystallizations than found elsewhere in the Cascade pluton.

The hornblende-biotite quartz diorite and tonalite that make up the western half and the border zones of the eastern half of the Cascade pluton consist of coarse-grained foliated rock in which black hornblende and biotite grains contrast with the light-bluish-gray mixture of plagioclase and quartz. This rock consists of about 60 percent plagioclase (An_{35-45}), 16–23 percent quartz, about 10 percent each biotite and hornblende, and 2–4 percent epidote. The common accessory minerals are magnetite, apatite, and sphene. There is very little or no potassium feldspar as shown by stained specimens (table 1). This rock differs from the quartz dioritic border zones described from the Pulga and Bucks Lake quadrangles (Hietanen, 1973a) mainly by its higher content of epidote.

Locally in the eastern part of the pluton, biotite forms large (½–1 cm long) round flakes subparallel to the plane of foliation (fig. 8). These large biotite flakes are especially common along Lost Creek and along Rock Creek. Part of the biotite-rich rock contains a small amount of potassium feldspar (locs. 1272, 1367); all have 25–27 percent quartz and are shown as tonalite in table 1.

Dikelike bodies of bluish-gray medium-grained rock that contain only a few scattered large round flakes of biotite occur in biotite tonalite parallel to its foliation along the South Fork of the Feather River near Boehme Ranch (just south of loc. 1367). The mineral content of this rock (loc. 1368b) and its host rock (loc. 1368a) is shown in table 1 (nos. 26, 25). The dike is mineralogically and presumably chemically similar to the trondhjemite. The gradational contacts and the occurrence of large biotite flakes suggest that it is a local differentiation product of biotite tonalite of the pluton, an association that has an important bearing on the origin of trondhjemitic magma. (Discussed under "Origin of Magmas.")

The outcrops along Fall River and those near the Lost Creek Reservoir contain 5–8 percent potassium feldspar and are classified as tonalite and monzotonalite according to Hietanen (1961) and a normative Ab-Or-An diagram (fig. 10). There is a complete gradation from quartz diorite to tonalite and to monzotonalite as quartz and potassium feldspar increase and the anorthite component of the plagioclase and hornblende decrease. The percentage of the dark constituents—biotite and hornblende—is generally 7–10 in the light-colored interior mass (nos. 21–25, table 1 and fig. 7) but 18–23 in the border zone.

Plagioclase in quartz diorite and tonalite shows two phases of crystallization: The euhedral to subhedral strongly zoned crystals (An_{43-36}) are early, and the

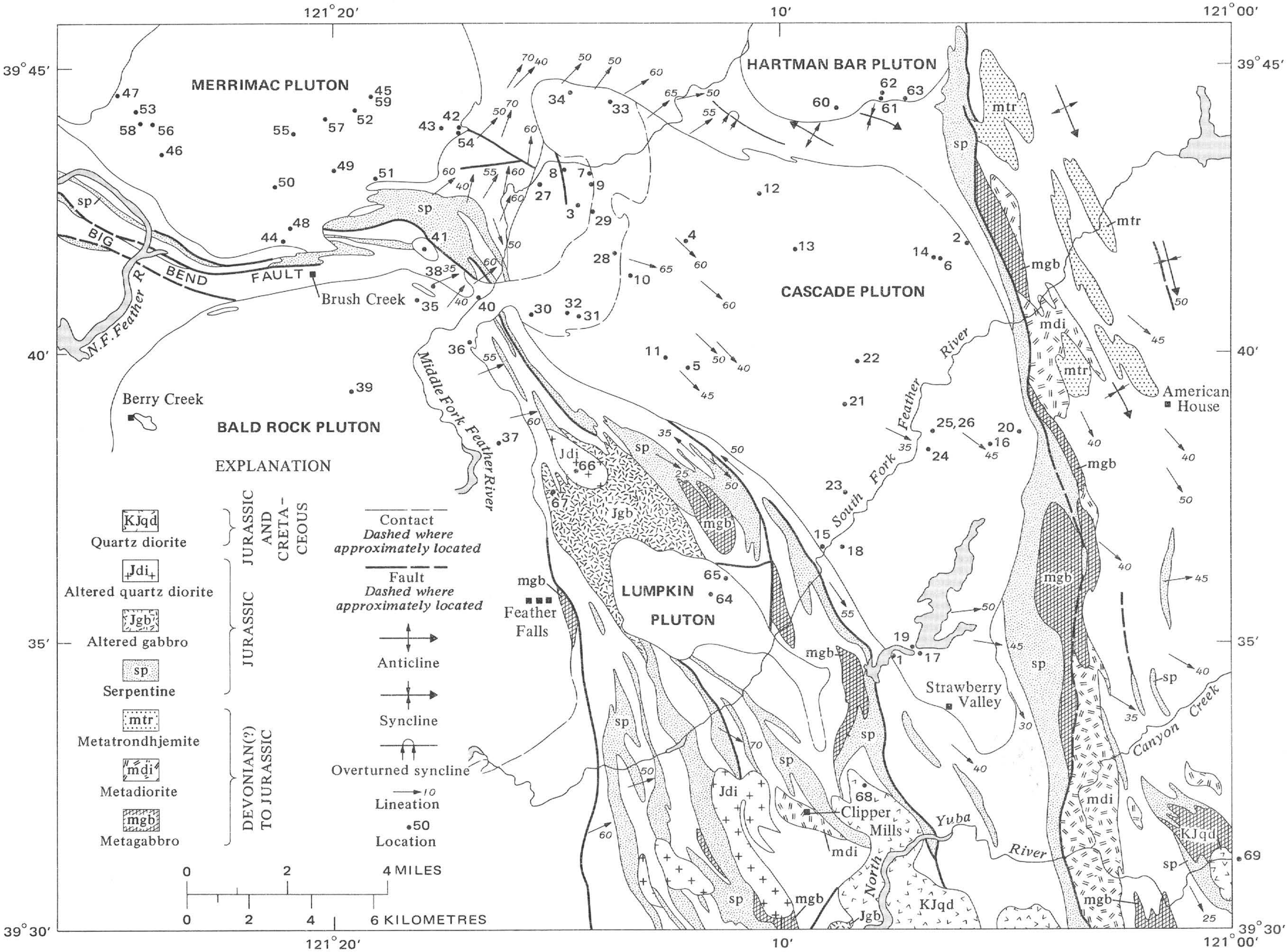

FIGURE 7.—Lineation in the Cascade pluton and vicinity and the location of stained specimens (table 1).

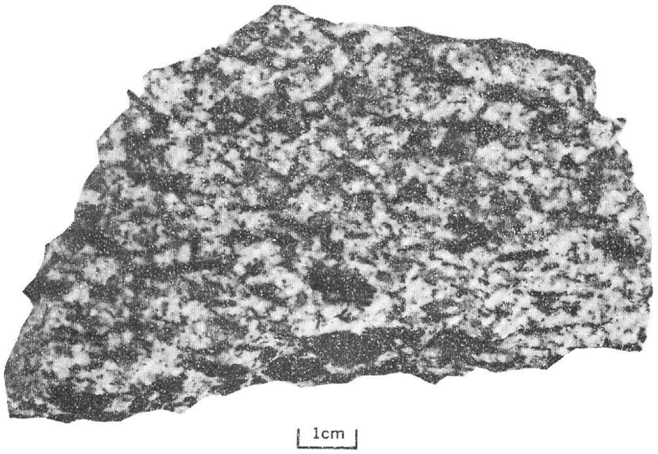

FIGURE 8.—Tonalite, containing large biotite flakes (black), from a logging road along Rock Creek on the southwestern part of the Cascade pluton (loc. 1272).

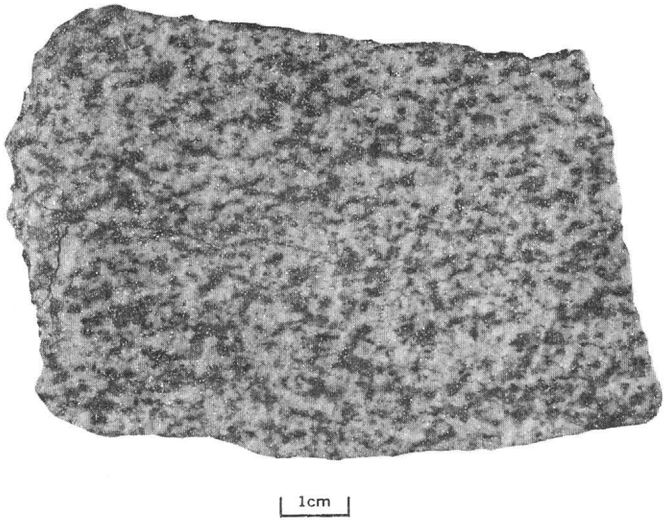

FIGURE 9.—Foliated trondhjemite from Watson Ridge, west-central part of area of geologic map (pl. 1).

anhedral twinned but not zoned grains (An_{36}) are later. Some of the zoned crystals were resorbed, then rimmed by a homogeneous more sodic plagioclase (An_{36}). The late plagioclase grains show polysynthetic complex twinnings (albite, Carlsbad, pericline, Ala). Both types may include hornblende.

Quartz is in interstitial grains ½–2 mm long that show weak strain shadows. Some granulation occurs locally. Clusters 3–8 mm in length are common.

Epidote is one of the major constituents in the Cascade pluton, forming 5–7 percent of most rocks. It occurs in two generations: (1) The early euhedral to subhedral crystals, many of which are included in biotite and hornblende or occur next to them. Many of those partly surrounded by biotite and hornblende are bounded by crystal faces toward these minerals but have irregular (resorbed?) borders against plagioclase and quartz. (2) The late epidote crystals rim some grains of hornblende and biotite or are clustered near them or included in plagioclase. A few euhedral crystals of allanite, ½–1 mm long and usually rimmed by epidote, are scattered through the rock.

Hornblende is in large (1–5 mm long) subhedral crystals that are strongly pleochroic: γ=bluish green, β=green, and α=pale green. In the western part of the pluton, small brown strongly pleochroic flakes of biotite occur with hornblende, both subparallel to the foliation. The large round flakes in the eastern part are much darker brown (γ=β=dark brown, α=light yellow brown) than the small flakes in the same rock. Minor alteration of biotite, more rarely of hornblende, to chlorite is common. In some of the monzotonalite along the Fall River, all the biotite is altered to chlorite that includes small brown crystals of rutile; plagioclase in this rock includes numerous tiny grains of epidote and muscovite.

Trondhjemite that cuts the western part of the Cascade pluton is chemically and mineralogically similar to the trondhjemite in the interior of the Bald Rock pluton (Hietanen, 1951; Compton, 1955). Most of the trondhjemite is medium grained to coarse, either foliated (fig. 9) or massive, very light bluish gray in fresh rock, and white in weathered outcrops. It consists of plagioclase, quartz, biotite, some muscovite, and potassium feldspar (table 1, nos. 27–34). Hornblende is absent or present in small quantities. The accessory minerals are magnetite and apatite.

Plagioclase is in subhedral stocky zoned crystals (3–6 mm long); many are twinned. The cores of the zoned crystals are commonly An_{30-35}, and a few are as calcic as An_{55}; the rims are An_{20-15}. Most of the quartz is in interstitial grains that are much smaller than the plagioclase crystals. Some quartz, however, forms large (10 mm long) oval clusters that consist of 5–6 large strained grains. A few of these have outlines suggesting that they were originally large individual quartz crystals. Potassium feldspar shows microcline grid structure and occurs with small grains of plagioclase and myrmekite between the large zoned plagioclase crystals. Muscovite and epidote occur with biotite subparallel to the foliation. Some of the biotite is altered to chlorite that includes rutile.

HARTMAN BAR PLUTON

The southern part of the Hartman Bar pluton consists mainly of hornblende-biotite quartz diorite and tonalite; a trondhjemitic light-brownish-gray rock is exposed along its southern margin. As the exposure is poor, it is not known whether this trondhjemite is a separate, later intrusion similar to the trondhjemitic tongue in the Cascade pluton. The stained specimens of this border phase (table 1, locs. 1281, 1282) contain very little if any potassium feldspar, 6–10 percent biotite, and about 40 percent quartz. The rock is coarse grained and slightly foliated.

Thin sections show that plagioclase (An_{25-27}) is zoned and twinned; some grains contain epidote and muscovite as alteration products. Quartz is interstitial or occurs in aggregates of strained grains, many elongate parallel to the foliation. Some small flakes of muscovite and grains of epidote are clustered with flakes of biotite (2–10 mm long) that are subparallel to the foliation. In contrast with the border zone on the north side of the pluton, where all the large biotite flakes are locally altered to chlorite and abundant epidote is common (Hietanen, 1973a), alteration of biotite to chlorite is rare.

A short distance from the border, the rock has less quartz and about 5 percent hornblende in addition to 15 percent biotite. As in parts of the Cascade pluton, biotite locally forms large round flakes. Some of the plagioclase crystals show strong oscillatory zoning; others have only a narrow more albitic rim around twinned grains that are An_{35-40}. Biotite is pleochroic in very dark brown to brownish yellow. Hornblende has γ=dark bluish green, β=green, and α=light yellow green. Small euhedral to subhedral crystals of epidote are included in biotite. Large anhedral grains of epidote are clustered with biotite and hornblende. Quartz is in fairly large grains (½–2 mm long) either interstitial or in monomineralic clusters 4–6 mm long and elongate parallel to the foliation. Magnetite, apatite, and zircon occur as accessory minerals. These textural and mineralogic features indicate that the quartz diorite of the Hartman Bar pluton is similar to that of the Cascade pluton, suggesting a comagmatic origin.

MERRIMAC PLUTON

The Merrimac pluton was dated by Grommé, Merrill, and Verhoogen (1967) at 130 m.y. (biotite 131 m.y. and hornblende 129 m.y.) on a sample collected near Coon Creek, 1½ km southwest of Merrimac, in the Pulga quadrangle. This Early Cretaceous date coincides with the end of the Yosemite intrusive epoch of Evernden and Kistler (1970) in the main Sierra Nevada batholith.

An age somewhat older than the Merrimac pluton is suggested for the Cascade pluton by certain differences in shape, structures, textures, and mineralogy of the two plutons. Whereas the Cascade pluton is strongly elongate with its longest dimension parallel to the trends, the Merrimac pluton is kidney shaped with its longest dimension perpendicular to the regional trends. The Merrimac pluton, like the Cascade pluton, has foliated quartz diorite border zones and grades to tonalite and monzotonalite toward the center. Foliation in the Merrimac pluton, however, is less pronounced, hypidiomorphic texture being more common and products of alteration and recrystallization fewer.

The southeastern border zone of the Merrimac pluton consists of coarse-grained hornblende-biotite quartz diorite that contains about the same amount of hornblende but much less epidote than this rock type in the Cascade and Hartman Bar plutons. Some of the plagioclase (An_{30-40}) crystals are subhedral, zoned, and twinned; others are anhedral, unzoned, and twinned and have compositions of An_{35-37}. Hornblende is pleochroic: γ=bluish green, β=green, and α=light green; it is clustered with biotite. Some aggregates of small hornblende crystals include many small round magnetite grains. Larger grains of magnetite are clustered with biotite and hornblende. Quartz is interstitial and shows weak strain shadows. Apatite, epidote, and zircon are included in, or are next to, the dark minerals.

Very little or no potassium feldspar occurs in most of the border zone. However, very light colored potassium feldspar-bearing quartz diorite occurs along the border zone about 1 km north of Mountain House and locally along the southwestern margin (loc. 1616, table 1). About 1–2 km from the border, potassium feldspar content is generally 4–6 percent and hornblende is less abundant. Toward the central part, the rock grades to tonalite and monzotonalite with 4–8 percent potassium feldspar (see fig. 7 for locations of specimens in table 1). In outcrops near Coon Creek, dark- and light-colored constituents are segregated into irregular layers in which the percentage of potassium feldspar ranges from 3 to 18 and that of the dark constituents in the corresponding layers 20–8 percent (locs. 1604, 1605, table 1). The average composition is similar to that of monzotonalite (loc. 1606, table 1).

An elongate mass of fine-grained brownish-gray quartz diorite occurs along the border of the Merrimac pluton just north of Mountain House. This diorite and two small bodies of gabbro in this vicinity, one of them enclosed by the pluton, may be of the same age as the Lumpkin pluton, which they resemble in their texture, color, and mineralogy.

MASS AT HAMPSHIRE CREEK

The plutonic rock at Hampshire Creek is the northern end of a large mass that extends southward to the North Yuba River and beyond. The outcrops east of the river consist of medium- to coarse-grained hornblende quartz diorite that includes some small bodies of hornblende gabbro. The border zones at Hampshire Creek are similar hornblende quartz diorite, but most of the central part consists of light-colored monzotonalite that contains as much as 40 percent quartz and 10–16 percent potassium feldspar. In texture and mineralogy, this rock resembles the monzotonalitic center of the Merrimac pluton except for more quartz in places at Hampshire Creek. Similar coarse-grained light-colored rock is exposed along the southern border of the map east of the main mass.

In the silicic rock at Hampshire Creek, small euhedral crystals of plagioclase (An_{25-28}) are embedded in a mixture of large grains of quartz, potassium feldspar, and biotite. The calcic cores of the plagioclase crystals contain alteration products, epidote and sericite; only the rims are clear. The accessory minerals are epidote, magnetite, and zircon.

MASS IN INDIAN VALLEY

Tonalite along the North Yuba River in the southeastern corner of the map (pl. 1) is a western part of a small mass that is well exposed farther east in Indian Valley. This tonalite is similar to tonalite in the Cascade pluton. Dark minerals, hornblende and biotite, contrast against the light-bluish-gray mixture of plagioclase and quartz. A part of hornblende and biotite occur as large euhedral to subhedral crystals. A sample from Indian Valley (table 1, no. 69) shows 57 percent plagioclase and 4.7 percent potassium feldspar.

BALD ROCK PLUTON

The eastern border zone of the Bald Rock pluton consists of foliated hornblende-biotite quartz diorite that is lighter in color than the border zone of the Cascade pluton and contains 2–7 percent potassium feldspar (table 1, locs. 1326, 1451). The stained specimens and thin sections show that this border zone is similar to the southeastern potassium feldspar-bearing border phase of the Merrimac pluton (table 1, locs. 1515, 1522). Well-developed foliation parallel to the contact and lineation down the dip were mapped by Compton (1955).

Thin sections show parallel orientation of dark minerals, bluish-green hornblende and brown biotite, and plagioclase in lath-shaped crystals oriented subparallel to the foliation. Quartz is interstitial and strained. Subhedral to anhedral small crystals of epidote occur next to the hornblende and biotite. Apatite, magnetite, and sphene are the accessory minerals. The monzotonalite at Feather Falls (loc. 1492), 1 km from the contact, is coarse grained and light colored. It contains 9–10 percent potassium feldspar and 13 percent dark minerals, mainly hornblende. Biotite includes crystals of sphene, apatite, and epidote. In the hornblende, γ=gray green, β=green, α=light green, and some grains are partly rimmed by epidote. Plagioclase (An_{25-30}) is weakly zoned and twinned. Sparse allanite is common.

Compton (1955, pl. 1 and p. 28) shows a sharp contact between this 3–4-mile-wide darker marginal phase and the trondhjemitic interior extending southward for about 10 km from 1 km south of Little Bald Rock. He considered it to be an erosion surface between the semicrystalline border and mobile magma of the core.

Coarse-grained very light colored trondhjemite is exposed in the gorge of the Middle Fork of the Feather River where it cuts through the metamorphic rocks. A stained sample (table 1, loc. 1461) shows 5.6 percent potassium feldspar and less than 4 percent dark minerals. A small body exposed at Shute Mountain about 1½ km to the northwest is of similar coarse-grained trondhjemite but contains very little, if any, potassium feldspar.

The contact of the Bald Rock pluton and a metatuff rich hornblende is exposed on a roadcut along Milsap Bar road. The plutonic rock next to the contact is strongly sheared and contains abundant quartz (table 1, loc. 1452). Biotite and minor hornblende are in trains parallel to the foliation. Magnetite, sphene, and epidote are clustered with the dark minerals. Plagioclase (An_{25}) and quartz are in round to elongate anhedral grains. Potassium feldspar is interstitial and some myrmekite occurs in places.

COMPOSITION OF THE PLUTONIC ROCKS

The ratios of percentages of quartz, feldspars, and dark minerals measured in the stained samples of plutonic rocks (table 1) were plotted as figure 10. The broken lines separate three rock types: quartz diorite, tonalite, and trondhjemite, on the basis of the percentage of dark minerals. In most, the potassium feldspar content is less than 10 percent, but in two of the monzotonalites (within the tonalite field) it is 15–18 percent. The distribution of points shows that in general all rocks contain 55–70 percent feldspar; quartz content in most quartz diorites is 14–25 percent, in tonalites 15–30 percent, and in trondhjemites 24–40 percent. Silicic rocks with about 10 percent potassium feldspar (no. 39) plot in the granite-trondhjemite field in a normative Ab-Or-An diagram (fig. 10; analysis M204 from Hietanen, 1951).

Local variation in potassium feldspar content is common in the central parts of all plutons. In the Grizzly pluton (Hietanen, 1973a) the percentage of the potassium feldspar in the light-colored interior is commonly 6–10 percent but may locally be as high as 17 percent or in places only 1 percent. In the southeastern central part of the Cascade pluton, potassium feldspar content ranges from a fraction of a percent in tonalitic rock to about 8 percent in monzotonalite. Many of the samples studied by Compton (1955) from the interior of the Bald Rock pluton contain more than 10 percent potassium feldspar and are granite-trondhjemites according to the normative subdivision by Hietanen 1961). Compton's samples 2 and 3 (1955, p. 30) have as much as 20 and 15 percent potassium feldspar, indicating a considerable range in the potassium feldspar content in the central part of the trondhjemitic Bald Rock pluton. The essential compositional difference between the Bald Rock pluton and the Cascade pluton is a larger amount of trondhjemite as an apparent end product of the crystallization in the Bald Rock pluton. The quartz dioritic rocks of the border zones in the two plutons are much alike and grade into similar monzotonalitic inner border zones. The main mineralogic difference is much larger amounts of epidote and biotite in the Cascade pluton, indicating a higher content of H_2O in the magma from which the older Cascade pluton crystallized.

Representative samples of the three age groups of postkinematic plutonic rocks were analyzed chemically (table 2). Quartz diorite (sample 1267) from the oldest group contains less alkalies and more iron than the quartz-dioritic border zones of the younger plutons (Hietanen, 1973a). Mineralogically, this difference is shown by a large amount of epidote in the oldest quartz diorite.

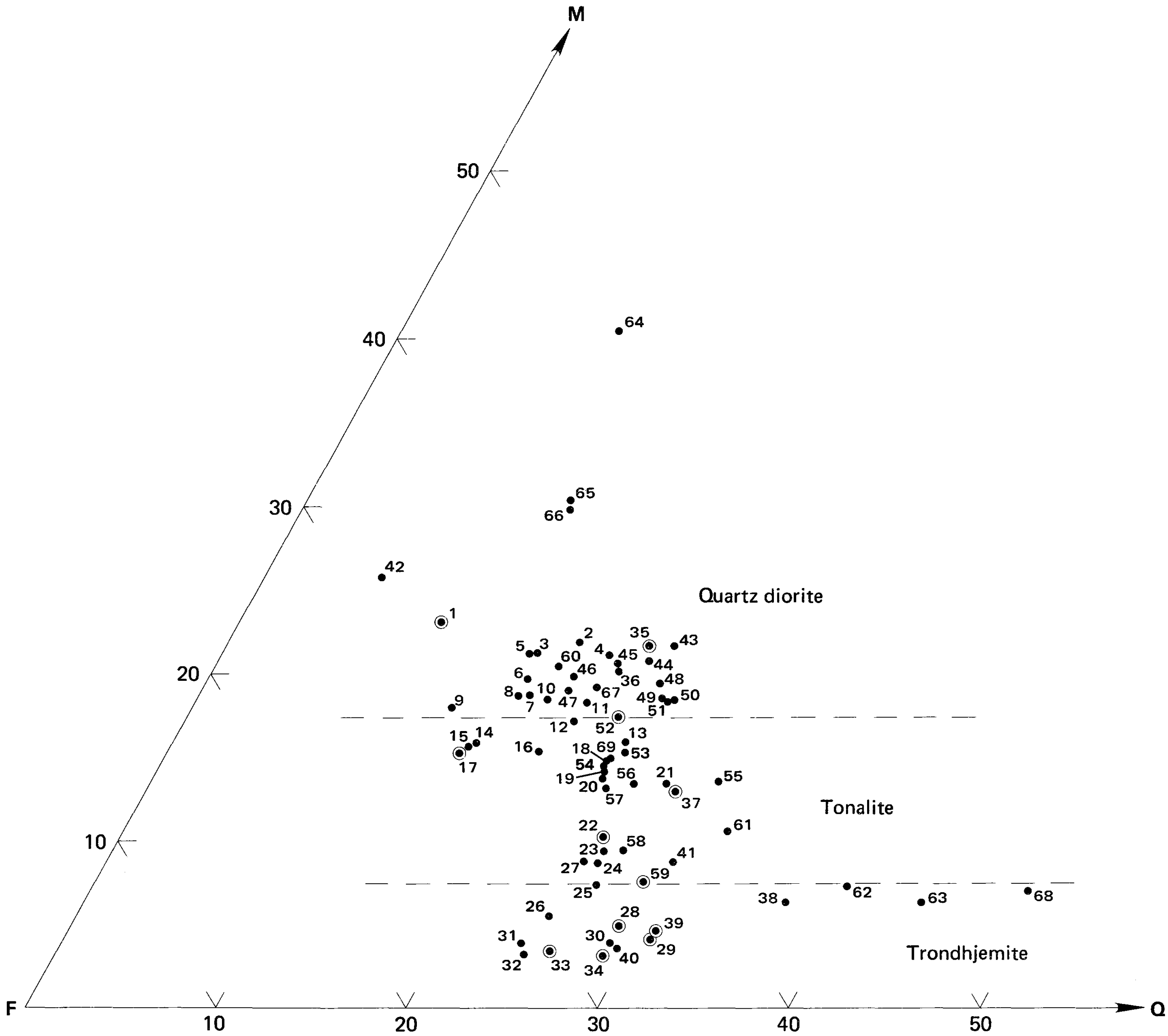

FIGURE 10.—Ratios of total feldspar (F), quartz (Q), and femic minerals (M) in stained specimens of plutonic rocks. Numbers refer to those in the first column in table 1. Specimens containing 7–18 percent potassium feldspar are encircled.

As shown by chemical analyses, the composition of biotite tonalite from the eastern part of the Cascade pluton (sample 1367, table 2) is similar to that of tonalite in the Granite Basin pluton in the Bucks Lake quadrangle. No analysis of the quartz dioritic western part of the Cascade pluton is available, but on the basis of its mineralogy, it is considered to be similar to the quartz dioritic border zones of the Bucks Lake, Grizzly, and Granite Basin plutons farther north (Hietanen, 1973a). The monzotonalitic rocks in the east-central part of the Cascade pluton (table 1, locs. 1271, 1450, 1555) are mineralogically and presumably also chemically similar to the central monzotonalites in the Grizzly, Oliver Lake, and Granite Basin plutons. These interior parts contain 2–3.5 percent K_2O and 4–4.5 percent Na_2O.

The chemical analysis of trondhjemite (table 2, sample 1313) shows more than 5 percent Na_2O and only 1.5 percent K_2O, a part of which is contained in biotite and muscovite. The potassium feldspar content is about 5 percent. The calcic cores of many zoned plagioclase crystals raise the CaO content to 2.7 percent. Comparison with light-colored biotite tonalite from the Cascade pluton (sample 1367, table 2) shows a lower percentage of MgO, FeO, and CaO and a higher percentage of SiO_2 and Na_2O in the trondhjemite, which has a much lower content of hornblende, biotite, and anorthite component and a higher content of quartz. The potassium content of trondhjemite is only slightly lower than that in the biotite tonalite, about 1 percent lower than that in the monzotonalitic parts of the interior, but much lower than that found earlier (Hietanen, 1973a) in the granitic parts of the Grizzly pluton (fig. 2).

The differentiation of the plutonic magma was from a quartz dioritic border to either a potassium-rich or a potassium-poor end product in the center. This splitting of the magma into two branches of differentiation is best illustrated in an Ab-Or-An diagram (fig. 11), where the new analyses are shown in relation to the trend line for the differentiation of the plutonic rocks in the Pulga and Bucks Lake quadrangles to the north (Hietanen, 1973a). The trondhjemites plot toward the Ab corner far from this trend line. Dikelike bodies of bluish-gray medium-grained trondhjemite (loc. 1368b) in biotite tonalite represent the local end product during the crystallization of tonalitic magma. The scarcity of potassium feldspar in this end product is partly due to impoverishment of magma in K_2O by crystallization of a large amount of biotite in the tonalite.

Trace elements (table 2) show trends similar to those in the plutonic rocks in the adjoining Pulga and Bucks Lake quadrangles (Hietanen, 1973a), supporting the suggestion that all plutonic magmas have the same parent magma. Ba and Sr increase with the increasing SiO_2, whereas the V, Cu, Co, Y, and Sc decrease. In comparison with the quartz diorites farther north, the hornblende quartz diorite from the Frey Creek mass is exceptionally low in Cr and Ni.

STRUCTURES AND EVOLUTION OF THE PLUTONS

Foliation is well developed parallel to the contact along most border zones of large plutons but becomes obscure toward the cores. It is considered to have been produced by the movement and pressure of the magma that was still rising in the center while the borders were crystallizing. In most plutons, the last-crystallized part of core is not in the center but conspicuously to one side, generally the east side, indicating, together with flow structures, that the plutons are tilted to the west. The intrusion most likely followed preexisting eastward-dipping structures.

From the description of the rock types in the Cascade pluton, it is clear that the history of this pluton is more complicated than that of most other plutons in the Feather River area (fig. 2). The zoned main mass has a foliation roughly concentric around the south-central part, the last to crystallize. The lineation plunges 45°–55° to the southeast, parallel to the major fold axes of the wallrocks, suggesting that their structures determined the direction of the invading magma. This structure, together with the strongly elongate shape, suggests that the pluton was emplaced earlier than most other plutons in the northwestern Sierra Nevada. The mineralogy, in particular the relative abundance

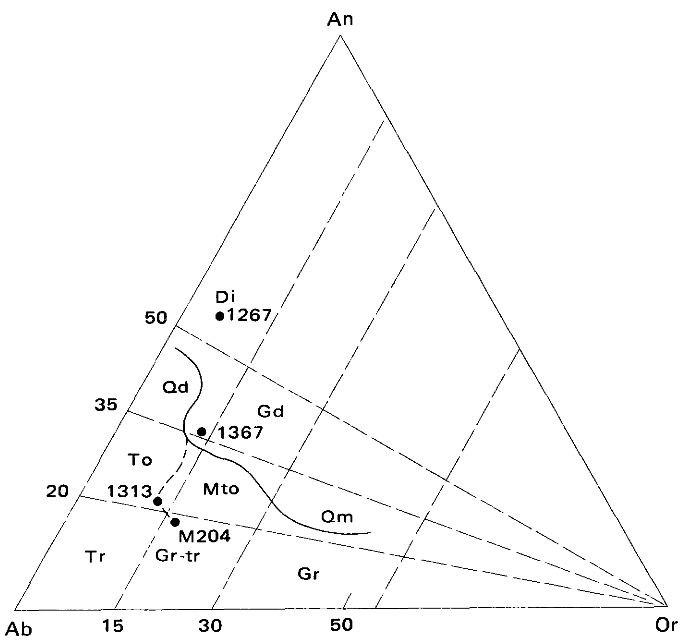

FIGURE 11.—Normative Ab-Or-An diagram showing points for new analyses in relation to the differentiation curve for the plutonic rocks in the Pulga and Bucks Lake quadrangles.

of epidote and other products of alteration, supports the concept of a somewhat older age and longer history. The trondhjemitic tongue that extends from the Bald Rock pluton eastward through its foliated border zone and through the metamorphic wallrocks, and farther east cuts the western border zone of the Cascade pluton discordantly, must have the age of similar trondhjemitic rocks in the interior of the Bald Rock pluton.

The trondhjemitic dikes that crystallized from the residual magma of the biotite tonalite in the eastern part of the Cascade pluton show crystallization differentiation in the Cascade pluton was from biotite quartz diorite to trondhjemite, a trend similar to that in the Bald Rock pluton except for a larger amount of biotite and less potassium feldspar. These relations suggest that the Cascade pluton is an earlier differentiate of the tonalitic magma from which the Bald Rock pluton was emplaced at a somewhat later phase. Together all the plutonic rocks probably span plutonic activity from the Late Jurassic to Early Cretaceous.

In contrast to the trondhjemitic trend in the Cascade and Bald Rock plutons, the differentiation in the plutons to the north of the study area, as in the Grizzly pluton (fig. 11), was toward a granitic composition, with an increase in the potassium feldspar content toward the silicic end members. None of the plutons in the study area (fig. 2), however, have granitic cores; rather, the dominant rock type in the centers is monzotonalite with a higher content of anorthite in plagioclase, a larger amount of biotite and hornblende, and less potassium feldspar than is common in granite. The percentage of potassium feldspar in the monzotonalite is similar to that in parts of the trondhjemitic core of the Bald Rock pluton; the percentages of dark constituents and the anorthite content of plagioclase are higher.

ORIGIN OF MAGMAS

The following three major groups of igneous rocks are recognized in the study area: Paleozoic metavolcanic rocks (early orogenic), Mesozoic plutonic rocks (late orogenic), and Tertiary volcanic rocks (postorogenic, Hietanen, 1972). A similar sequence of magma generation from early volcanism to plutonism during the orogeny and a later postorogenic volcanism is common in most orogenic belts. These three groups have distinctive chemical and mineralogic characteristics that suggest different origins. A short summary of the geologic history of the Feather River area provides some information that could lead to a better understanding of the relations between the magma types and the tectonic environment in which they were generated.

ISLAND-ARC-TYPE VOLCANIC ROCKS

The earliest igneous rocks extruded during the deposition are volcanic and volcaniclastic rocks of the andesite-sodarhyolite suite, mapped as the Franklin Canyon Formation. Some of these rocks in the Bucks Lake quadrangle rest on a sequence of interbedded metachert and phyllite (the Calaveras Formation), indicating a younger age for the metavolcanic sequence. The main metavolcanic unit is southwest of the Calaveras belt and is bordered by faults, the Dogwood Peak fault on the northeast and the Camel Peak fault on the southwest. Displacement along the Dogwood Peak fault was probably minor, for in the Bucks Lake quadrangle (Hietanen, 1973a) meta-andesite similar to that of the Franklin Canyon Formation overlies the rocks of the Calaveras Formation on the northeast side of this fault. Moreover, there are no ultramafic rocks along it, as there are along all the other major faults. An inhomogeneous sequence of interbedded metavolcanic and metasedimentary rocks (the Horseshoe Bend Formation) that includes minor discontinuous limestone beds is exposed southwest of the Franklin Canyon Formation. Field relations in the Pulga quadrangle suggest that the Horseshoe Bend is the younger.

The andesite-sodarhyolite suite (the Franklin Canyon Formation), here considered probably correlative with the Devonian island-arc-type andesites of the Klamath Mountains, was deposited on a sequence of interbedded chert and shale, which are typical sediments on the ocean floors. This stratigraphy is compatible with that in the tectonic environment of island arcs along the continental margin as postulated for the Devonian by Burchfiel and Davis (1972, p. 102). The andesitic volcanism in the Feather River area was followed by deposition of volcanic, volcaniclastic, and sedimentary rocks (the Horseshoe Bend Formation) that include minor carbonate layers indicating deposition in shallow water. Most rhyolites of this period, probably Permian, are rich in potassium feldspar rather than in albite, as in the Franklin Canyon Formation.

The formations exposed in the successive fault blocks to the west (fig. 2) are progressively younger. This progression, together with overturning of the folds to the southwest, can be considered as surface expression of a large-scale underthrusting to the east, consistent with the concept of subduction of the Pacific Ocean floor under the North American continent during Paleozoic and Mesozoic time (fig. 12). The trace of the subduction zone would be west of the area of figure 2, most likely in the Coast Ranges, where the common occurrence of glaucophane schists indicates high pressures and low temperatures during metamorphism. The andesitic magmas that gave rise to island-arc-type volcanism in the Devonian originated above this subduction zone (Hietanen, 1973b).

Before the introduction of the concept of plate tectonics, calc-alkalic andesite was generally considered to be a derivative of basaltic magma either through fractionation (Kuno, 1968) or by contamination from sialic material. The hypothesis of contamination in the island arcs is refuted by the thinness of the crust there. Uniformly low Sr^{87}/Sr^{86} ratios typical of all island-arc-type andesites also tend to refute this hypothesis, as pointed out by Taylor (1969) and McBirney (1969). In the light of plate tectonics, it has been suggested that calc-alkalic andesite magma is derived by melting of the oceanic lithosphere (Dickinson, 1970) or by partial melting of mantle peridotite under hydrous conditions (Yoder, 1969).

Seismic studies on the modern island-arc systems show that the descending sea floor can be traced as a high-velocity lithospheric slab to depths of 350 and 700 km (Isacks and others, 1969; Barazangi and others, 1970; Yoder, 1971). The slab stays rigid and cooler than the surrounding mantle, making it improbable that the andesitic magmas of the island arcs would be generated by melting of the downgoing oceanic lithosphere. It is clear that long before this slab reaches temperatures at which andesite begins to melt, it undergoes certain chemical changes such as loss of water and other volatiles from the sediments attached to the sea floor and from hydrous minerals in the oceanic crust. The water ascends to the peridotitic mantle of the upper plate above (1a in fig. 12 and Hietanen, 1973b), causing there two critical changes as shown by the experimental work of Yoder (1969): The water lowers the temperature at which the peridotite begins to melt by about 250°C. The composition of the first melt is andesitic and not basaltic, as it would be in anhydrous conditions and at higher temperatures from the same parent peridotite (Yoder and Tilley, 1962).

Both volcanic suites in the study area include silicic lavas, conventionally considered to be products of fractional crystallization. It has been pointed out that metasodarhyolite and metadacite appear to underlie the meta-andesite of the Franklin Canyon Formation, indicating that volcanism started with extrusion of sodarhyolite. This sequence of events agrees with the hypothesis of magma formation by fractional melting. In the Horseshoe Bend Formation, discontinuous layers of metarhyolite containing a considerable amount of potassium are interlayered with metabasalt, suggesting more or less contemporaneous extrusion.

Yoder (1973) has suggested a possible mechanism for the generation of silicic and basic magmas from a common parent rock, such as the rocks in the mantle. The first liquid to form at elevated temperatures is silicic. This silicic liquid continues to form until all available quartz is exhausted. With removal of the silicic melt, the composition of the remaining parent rock becomes increasingly more mafic, thereby requiring an elevation of temperature for the resumption of its melting. The liquid formed at this second stage of fractional melting is andesitic in hydrous conditions but basaltic in anhydrous conditions, the basaltic liquid requiring a higher temperature.

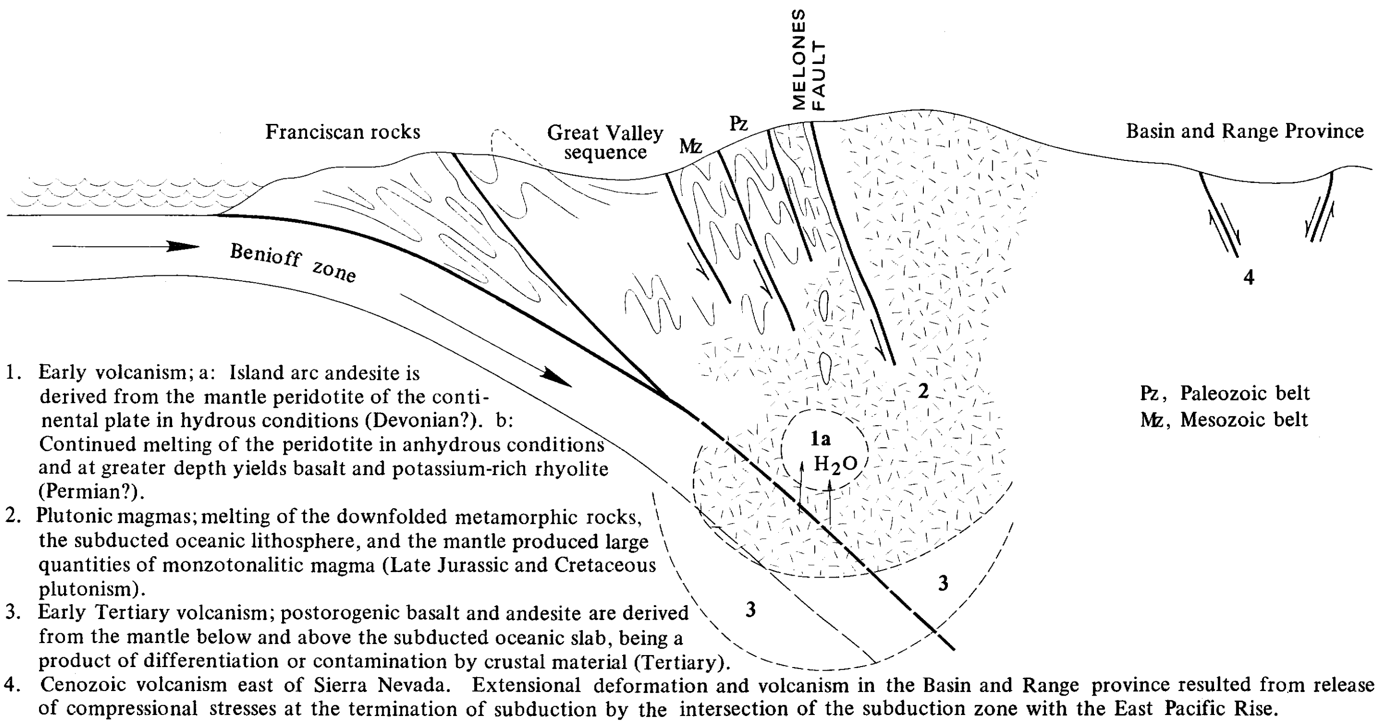

FIGURE 12.—Evolution of magmas in the northern Sierra Nevada.

Nothing was said by Yoder (1973) about the possible variation in the potassium content of the silicic melts formed in the first stage of fractional melting. This appears to be a crucial point in the generation of Devonian(?) and Permian(?) magmas in the study area, as it was during the Cenozoic volcanism in western North America in general (Dickinson and Hatherton, 1967; Dickinson, 1970; Lipman and others, 1972).

Dickinson and Hatherton (1967) and Dickinson (1970) have plotted the potassium content in volcanic rocks with various silica contents relative to the depth of the inclined seismic zones beneath the volcanoes in active Cenozoic island arcs and marginal continental ranges of the circum-Pacific orogenic belt. Comparison of the metavolcanic rocks of the Feather River area with their diagrams would suggest, after allowing for the changes due to metamorphism, that the potassium-poor andesite-sodarhyolite suite of the Franklin Canyon Formation (Devonian?) originated from a shallower depth than the younger potassium-rich lavas of the Horseshoe Bend Formation (Permian?). The dacitic and sodarhyolitic rocks analyzed contain 1–0.2 percent K_2O (Hietanen, 1951, 1973a), which unmodified, and applying Dickinson's (1970) plots of potassium content (K) relative to depth of magma chambers (h) for active Quaternary volcanic island arcs, yields depths of 50–100 km for the loci of generation of silicic magmas of the Franklin Canyon Formation. In contrast, the rhyolites of the Horseshoe Bend Formation contain 2–4 percent K_2O, yielding depths of 150–300 km according to Dickinson's scheme for the inclined seismic zone. The deeper level could have resulted from thickening of the upper plate above the magma chamber, either by accumulation of volcanic and sedimentary material and deformation of the upper plate (Hietanen, 1973b) or by thicker parts of the wedge-shaped upper plate overriding the heat source, or both.

Why does the potassium content of the magmas increase with depth of the magma chamber, thus with the increase in the pressure and temperature of the magma generation? The experimental work by Tuttle and Bowen (1958) on the fractional crystallization of granitic magma is illuminating. Tuttle and Bowen (1958, p. 78) showed that in the ternary system albite-orthoclase-quartz, the eutectic moves toward the quartz-albite sideline with increasing water-vapor pressure. The first liquid formed by fractional melting from the mantle in hydrous conditions would therefore be a sodium-rich rhyolite, followed at higher temperatures by an andesite liquid. The later (Permian?) magmas were generated from the mantle peridotite that had lost most of its water during the earlier period. The first Permian(?) liquids were therefore normal rhyolites with 2–4 percent K_2O, and the basic magmas were basaltic. The lower water-vapor pressure at this second stage was coupled with higher total pressure that resulted from an increased load above. Higher temperature is indicated by the basaltic composition of the melt.

An alternative explanation is based on the stability relations of amphiboles and micas. Experimental work by Modreski and Boettcher (1972) and Allen, Modreski, Haygood, and Boettcher (1972) show that whereas amphibole is decomposed below depths of 75 km, phlogopite is stable to depths of 100–175 km under the conditions of the low geothermal gradients anticipated in a relatively cool subducting oceanic lithosphere. Accordingly, mainly Na and H_2O would be released into a melt at depths of 60–90 km, and K would be tied up in phlogopite and become available only at deeper levels.

MONZOTONALITIC MAGMA

The deformation caused by postulated subduction of the oceanic plate under the continental plate during the Paleozoic and early Mesozoic came to an end late in the Jurassic Period, about 148 m.y. ago, which was the approximate beginning of local major plutonism and a major Sierran plutonic event that culminated in the Cretaceous (Kistler and others, 1971). The problem of the origin of the granitic magmas from which the plutonic rocks crystallized is universal and has been much disputed. In the Feather River area, the mean composition of the Cretaceous plutonic rocks is not truly granitic, but monzotonalitic (Hietanen, 1961), containing less SiO_2 and K_2O and more CaO, FeO, and MgO than the normal eutectic granites (Tuttle and Bowen, 1958). The trace-element content of the plutonic rocks is different from that of the regionally metamorphosed igneous suites (Hietanen, 1973a), indicating a different origin for these two magma series.

Partial melting of an oceanic plate as it descends to the mantle may take place eventually, giving rise to the generation of calc-alkalic magmas. The processes involved could be akin to those suggested by Green and Ringwood (1969) for the partial melting of quartz eclogite, basalt, and amphibolite on the basis of their high-pressure experimental studies. According to these investigators, calc-alkalic magma could be produced in the descending oceanic slab by partial melting of quartz eclogite at depths of 80–150 km and by partial melting of amphibolite (derived from basalt) and gabbro at depths of 30–40 km. Chemical changes in the folded and recrystallized metavolcanic rocks in the study area, however, suggest that the metamorphic complex above the magma chamber was involved in the processes of magma generation.

Comparison of the present composition of the metavolcanic rocks (Hietanen, 1951, 1973a) with

Daly's (1933), McBirney's (1969) and Chayes' averages (1969) for andesites shows that meta-andesites may have lost much of their potassium and silicon and have been greatly enriched in calcium, iron, and magnesium. The mineralogy and texture of the metavolcanic rocks suggest that these changes in composition took place during the metamorphism. For example, metadacites still have crystals of quartz that were slightly granulated during the deformation but are still recognizable as former euhedral phenocrysts. The rest of the rock is completely recrystallized, consisting now of epidote, amphiboles, albite, and quartz without any potassium-bearing metamorphic minerals. Large amounts of epidote and amphiboles that formed stable mineral assemblages with albite at low to medium metamorphic temperatures raise the percentages of CaO, FeO, and MgO to levels 3–5 percent higher than those common in average dacite. The sodium (and silicon) content of the metadacite is considerably lower than that of an average dacite, and there is only a fraction of a percent K_2O in the metadacite. There must have been an extensive migration of silicon and alkalies, particularly of potassium out of the metadacite during its metamorphism. Similar chemical changes occurred during the metamorphism of andesites, which, relative to average andesites, were enriched in CaO (4–9 percent), FeO (3.4 percent), and MgO (4 percent) and impoverished in Na_2O (1–2 percent), K_2O (2 percent), and SiO_2 (10 percent. Al_2O_3 content remained remarkably unchanged.

The mean composition of the plutonic rocks is close to monzotonalite that contains about 4 percent CaO, 2 percent FeO, 1.5 percent MgO, 4.5 percent Na_2O, 1.8 percent K_2O, 66 percent SiO_2, and 16 percent Al_2O_3. Comparison of this composition with that of an average andesite shows 1–2 percent less CaO, FeO, and MgO and more SiO_2 and Na_2O in the monzotonalite. Had the monzotonalitic magma formed by melting of primary basaltic rocks, the differences would be even greater, and there would not be sufficient K_2O. It cannot be a mere coincidence that the elements lost (K, Na, Si) and gained (Ca, Fe, Mg) by the volcanic rocks during their metamorphism are those that should be added (K, Na, Si) and subtracted (Ca, Fe, Mg) from andesitic and basaltic rocks to yield a monzotonalitic composition. Rather, these changes tended to reestablish the geochemical equilibrium in the metavolcanic-metasedimentary complex when it was warped down to high temperatures during the Jurassic deformation and a eutectic melt started to form. The melting process, which produced large quantities of magma, must have occurred during the regional metamorphism (contemporaneous with the deformation) to account for the chemical exchange of elements between the magma and the surrounding metavolcanic-metasedimentary complex. An Sr_{87} /Sr_{86} ratio higher than that in the mantle-derived basalt and andesite, but considerably lower than that in the sedimentary rocks, as found by Hurley, Bateman, Fairbairn, and Pinson (1965) for the Sierra Nevada plutonic rocks, is in agreement with the postulated mixed origin.

The metamorphic assemblages (andalusite-staurolite and andalusite-cordierite) in the pelitic layers indicate that the metamorphism was at pressures lower than the triple point of the aluminum silicates and at temperatures higher than the upper stability limit of staurolite. The temperatures about 600°C and pressures of 4 kb seem reasonable and could have been reached 12–15 km below the surface. The region of melting was at the lower level. Monzotonalitic magma would form by differential melting at about 700°C (Piwinskii, 1968) at depths of 25–30 km, assuming geothermal gradients of 30°–25°C/km. The mineralogic features of the plutonic rocks indicate that the monzotonalitic magma had a high H_2O content and was most likely formed close to the solidus temperatures. Textures of the plutonic rocks suggest that this magma was never completely liquid but contained crystals of plagioclase (An_{40-45}), epidote, hornblende, and biotite. Oscillatory zoning and resorption of early plagioclase phenocrysts indicates fluctuation of the physical conditions and possibly of the composition of the melt. A notable mineralogic feature is inclusions of euhedral epidote in biotite. This epidote must have crystallized earlier than the biotite that includes it. Moreover, the half-enclosed epidote crystals are bounded by crystal faces only on the biotite side; the side surrounded by plagioclase is anhedral, probably because of resorption. It is possible that the large amount of early epidote was inherited from metavolcanic rocks that were consumed by the magma. The excess of incorporated epidote could have recrystallized with euhedral shapes in a crystal mush in which most of the epidote was used up by plagioclase.

The large round biotite flakes in the biotite tonalite are early and may have lost their euhedral shapes by resportion. The metarhyolite with euhedral (pseudohexagonal) biotite phenocrysts (fig. 3) north of Mountain House is a close effusive equivalent of the biotite tonalite. The biotite-rich rhyolite has only a few small phenocrysts of quartz and albite. Biotite crystallized early, and the rest liquid was impoverished in potassium, yielding a trondhjemitic composition to the last differentiate, as evident in the late trondhjemitic dikes that cut the biotite tonalite in the Cascade pluton.

TERTIARY VOLCANIC ROCKS

Volcanism in the northern Sierra Nevada recommenced in Miocene time by extrusion of andesitic pyroxene basalt flows, the Lovejoy Basalt, and was followed by the eruption of pyroclastic andesite in which phenocrysts are plagioclase, hornblende, and augite. The youngest flows are olivine basalt and two-pyroxene andesite. There is every gradation from olivine basalt through two-pyroxene basaltic andesite to silicic hypersthene andesite, as described earlier (Hietanen, 1972), proving that Kuno's (1968) suggestion for the origin of andesite by differentiation from basaltic magma is valid here. The olivine basalt and its andesitic derivatives were extruded late in the Tertiary after the crust had thickened by deformation and plutonism. The postorogenic andesites have a different origin and more complicated history than the island-arc-type andesites. Using the potassium content of the parent basalt (0.8 percent, Hietanen, 1972) and Dickinson's (1970) K-h plot suggest depths of 120–230 km for the subduction zone near which the Tertiary basalt magma was generated. A 45° angle for the descent of the oceanic plate would bring the associated trench to the belt of glaucophane schists in the Coast Ranges (fig. 12).

MAGMAS IN SPACE AND TIME

This discussion has shown that in the mobile belts the composition of magmas depends on the tectonic environment in which they are generated and that this composition changes with geologic time. Good examples are the two distinctive types of andesites, the Paleozoic island-arc type and the postorogenic (Tertiary) andesites of this area. Moreover, the experimental work by Yoder (1969) and Green and Ringwood (1969) suggests that the calc-alkaline andesite magma may be generated in different ways at different geologic times, the mode of origin changing with the changing physicochemical conditions in the orogenic belts.

In general, four processes, supported either experimentally or by natural occurrences, may operate in orogenic belts through geologic time:

1. At an early stage, island-arc-type low-potassium andesite is generated from the mantle above the Benioff zone. Water from the descending sea floor ascends to the mantle above, lowering the melting point of peridotite. The first melt is andesitic, as demonstrated by the experimental work of Yoder (1969) and Kushiro (1972). After exhaustion of water, the composition of the melt is basaltic (Yoder and Tilley, 1962), and silicic lavas may be derived from this basalt by fractionation, or, with the presence of water, a silicic melt may be produced first, and after quartz is exhausted, the melt, which requires a higher temperature, will be basaltic (Yoder, 1973).
2. At a later stage, calc-alkaline andesite and related magmas may be generated by partial melting of quartz eclogite, amphibolite (derived from basalt), or gabbro in the downgoing oceanic lithosphere and in the base of the thickened crust (Green and Ringwood, 1969). Much of these magmas may not have vented to the surface but, rather, joined the plutonic magmas formed by partial melting of the crust and downfolded metamorphic rocks to produce large quantities of monzotonalitic magmas.
3. Late-stage magmas are produced by fractionation of basaltic magmas in either hydrous or anhydrous conditions (Green and Ringwood, 1969; Kuno, 1968) or by contamination of basaltic magma by crustal material. Late Tertiary two-pyroxene andesites in the northern Sierra Nevada were derived from tholeiitic basalt magma by fractional crystallization of olivine (Hietanen, 1972).
4. The latest stage magmas, late Cenozoic basaltic lavas east of the Sierra Nevada, are related to an extensional deformation typical of interarc basins behind the island arcs (Karig, 1971). An interarc-type spreading in the Basin and Range province was a direct result of the termination of subduction of the Pacific floor under the North American continent. Scholz, Barazangi, and Sbar (1971) have suggested the following mechanism: Partially melted material from the upper part of the subducting slab rises diapirically through the mantle, is trapped beneath the lithosphere, flattens there, and spreads outward. Extensional deformation and volcanism occur when the stress is released.

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