Pre-Cenozoic Geology of the South Half of the Auburn 15-Minute Quadrangle, California

GEOLOGICAL SURVEY BULLETIN 1341

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By F. H. OLMSTED

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Description of the crystalline rocks of an area in the foothills of the northern Sierra Nevada

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PRE-CENOZOIC GEOLOGY OF THE SOUTH HALF OF THE AUBURN 15-MINUTE QUADRANGLE, CALIFORNIA

By F. H. OLMSTED

ABSTRACT

The south half of the Auburn 15-minute quadrangle in the foothills of the northern Sierra Nevada includes parts of a quartz diorite pluton, a trondhjemite pluton, a steeply dipping sequence of metamorphic rocks, concordant to nearly concordant bodies of ultramafic and mafic plutonic rocks, and many small dikes and sills ranging in composition from diabase to granite pegmatite. Unconformably overlying these pre-Cenozoic crystalline rocks are thin, inextensive, and gently dipping pyroclastic and epiclastic deposits which were not investigated in detail.

The metamorphic rocks consist chiefly of volcanic flows and pyroclastic rocks of mafic and intermediate composition, which are metamorphosed to the almandine-amphibolite facies; metavolcanic rocks of the greenschist facies are exposed near the northeastern corner of the area. Locally interbedded with these metavolcanic rocks are subordinate metamorphosed silicic tuff and epiclastic rocks and crystalline limestone.

The ultramafic and mafic plutonic rocks generally are altered or metamorphosed to varying degrees and were intruded before the final episodes of folding and faulting. By contrast, the quartz diorite and trondhjemite plutons, herein named respectively the Penryn and Rocklin plutons, appear to have been intruded after the last major folding. The Penryn and Rocklin plutons have been dated by the potassium-argon method as 136 and 131 million years, respectively.

The metamorphic terrane is characterized by steeply eastward dipping to vertical schistosity and bedding. Dominant features are several steeply dipping large faults and fault zones marked by highly fissile chlorite schist and branching networks of phyllonite enclosing lensoid prisms of unsheared rock.

INTRODUCTION

The south half of the Auburn 15-minute quadrangle is in the foothills of the northern Sierra Nevada, northeast of Sacramento, Calif. (fig. 1). The area lies just east of the gently dipping Cenozoic deposits of the Sacramento Valley and is underlain chiefly by pre-Cenozoic metamorphic and plutonic rocks.

The main purposes of this study were to refine at a larger scale a part of the geology mapped by Lindgren (1894) in one of the

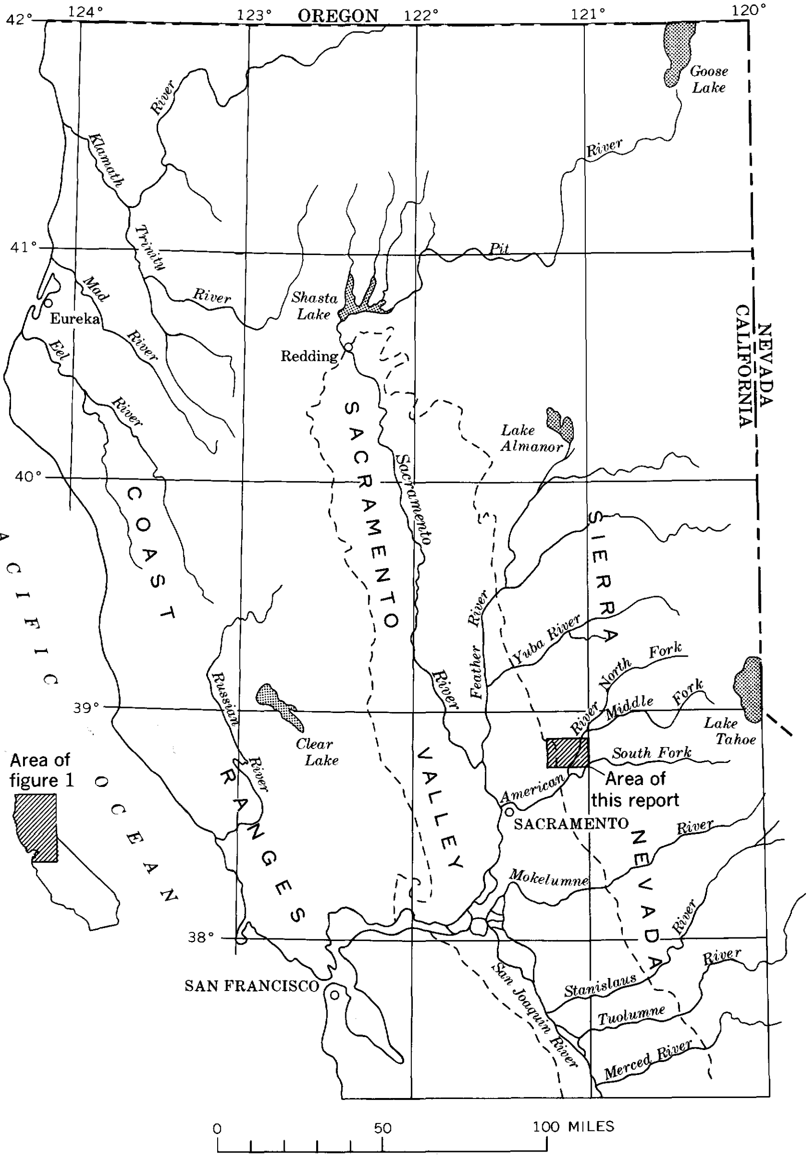

FIGURE 1.—Index map of northern California showing location of area mapped.

Gold Belt Folios of the U.S. Geological Survey and to present new information on the structure and composition of the pre-Cenozoic metamorphic and plutonic rocks. Sparse thin Cenozoic pyroclastic and epiclastic rocks were not investigated in detail and are not described.

The geology of a small area in secs. 22, 23, and 26, T. 12 N., R. 8 E., is based in part on unpublished mapping by the U.S. Bureau of Reclamation (1957) ; that of the ultramafic body at Flagstaff Hill in secs. 16, 20, 21, 27, 28, 29, and 33, T. 11 N., R. 8 E., is in large part modified from Wells, Page, and James (1940) and Cater, Rynearson, and Dow (1951). The interpretation of the origin of the Pine Hill intrusive complex at the southeastern corner of the area is based on the findings of Emerson (1969) and Springer (1969).

The topography is gentle in exposures of quartz dioritic rocks in the western part of the area, whereas exposures of metamorphic and ultramafic and mafic plutonic rocks to the east are more rugged and are characterized by ridges and ravines parallel to major north to northwest structural trends. Altitudes range from about 200 feet above sea level in the southwest to more than 1,800 feet at Pilot Hill, near the eastern margin of the area. Near the northern and western borders of the area, concordant flat-topped ridges underlain by resistant andesitic breccia and conglomerate of Tertiary age slope about 100 feet per mile toward the west and southwest.

Nearly continuous exposures along the American River and its tributaries reveal geologic details which generally are not discernible in the extensive interstream areas where outcrops are small and scattered and soils and weathered zones are deep and extensive. Consequently, many contacts are inferred from widely scattered exposures, and many small rock bodies and structural features that could have been shown at the scale of the geologic map (pl. 1) probably have been overlooked.

The fieldwork was made possible by the interest and cooperation of the many ranchers and other property owners who permitted access to their lands. Bryn Mawr College provided laboratory and library facilities and financial support. Professors Edward H. Watson and Dorothy Wyckoff directed the later phases of the study and gave valuable advice and encouragement.

REGIONAL GEOLOGY

The northern Sierra Nevada contains a broad belt of metamorphosed sedimentary and volcanic rocks of Paleozoic and Mesozoic age intruded by Mesozoic plutonic rocks. Major structures in the northwestern Sierra are roughly parallel to the main axis of the range (about N. 15° to 20° W.) but a more northerly trend dominates in the north-central part, and the strike of the metamorphic rocks is deflected around several plutons. Schistosity and axial planes of folds in the metamorphic rocks generally dip between 60° and 90° E.; at many places these structural features are parallel or nearly so. In the early Gold Belt Folios of the U.S. Geological Survey (Lindgren, 1894; Lindgren and Turner, 1894), the structure was interpreted as being homoclinal. However, more recent, detailed studies southeast of the area of this report (Taliaferro, 1943; Taliaferro and Solari, 1949; Clark, 1954; and Eric and others, 1955) have delineated tight folds which are nearly isoclinal at some places. Cleavage and foliation diverge substantially from bedding in some of the less deformed rocks.

Almost no faults are shown in the Gold Belt Folios, but more recent studies, summarized by Clark (1960), have identified major faults and fault zones approximately parallel to other regional structures. A reconnaissance study by Clark (1960) established the existence of a large system of steeply dipping faults which he designated the "Foothills fault system," in which the component faults are marked by zones of cataclastically deformed and recrystallized rocks, truncated folds, and major stratigraphic discontinuities. (An alternative explanation for the cataclastic zones has been given by Baird (1962), who ascribes these features to "penetrative slip folding.") According to Clark (1960), the faults cut rocks as young as Late Jurassic and are in turn interrupted or truncated by plutons ranging in age from Late Jurassic to early Late Cretaceous. Two major faults of this system are within the south half of the Auburn quadrangle, and another fault, farther south, is truncated by the younger of two quartz dioritic plutons lying partly within the area of this report (Clark, 1960, pl. 1). Relative movement on most of the faults has not been determined, but Clark believes that horizontal displacement on some may be measured in miles and that the relative movement may be left-lateral.

The metamorphic rocks of the western belt in the northern Sierra Nevada, including most of those in the area of this report, are chiefly of Mesozoic age; the metamorphic rocks to the east are chiefly Paleozoic (Strand and Koenig, 1965). These rocks were regionally metamorphosed during the Late Jurassic. Emplacement of the plutons during the Late Jurassic or Early Cretaceous caused further metamorphism, especially in contact aureoles.

METASEDIMENTARY ROCKS

The metasedimentary rocks are classified in two units on the geologic map (pl. 1) : (1) crystalline limestone, and (2) metasedimentary rocks undivided. The first unit consists of two bodies of crystalline limestone east of Rattlesnake Bridge. The second unit is heterogeneous, including phyllite, quartzite, and other rocks of epiclastic origin, and thin beds of metavolcanic rocks and crystalline limestone. The metasedimentary rocks constitute only a minor part of the metamorphic terrane, which is composed chiefly of metavolcanic rocks.

CRYSTALLINE LIMESTONE

The crystalline limestone in the two long lenticular bodies east of Rattlesnake Bridge is white to light gray and consists chiefly of medium to coarsely crystalline calcite. The larger, western mass is as much as 55 meters thick and dips 75° to 80° E., parallel to the schistosity of the enclosing amphibolite. This body, which for a long time has been quarried for lime, contains irregular lenses of schistose amphibolite and chlorite schist which are reported to hinder the quarrying operations (Clark and Carlson, 1956, p. 452). Some of the schist appears to be interbedded with the crystalline limestone, although both limestone bodies are in a major fault zone, so that some of the schist may occur in fault slices.

METASEDIMENTARY ROCKS UNDIVIDED

Metamorphosed epiclastic rocks and thin beds of metavolcanic rocks and crystalline limestone are scattered throughout the metamorphic terrane. The larger, better exposed zones are shown on the geologic map (pl. 1) as metasedimentary rocks undivided, but many zones are too thin or too poorly exposed to differentiate from the associated metavolcanic rocks.

Gray to greenish-gray phyllite is the most abundant rock type observed. Common constituents are quartz, sericite, albite, chlorite, biotite, magnetite, pyrite, and limonite; generally not all of these are present in a single specimen. Well-developed cleavage parallel to the original bedding (S_1) is most common, although an S_2 plane is defined locally by axial planes of small crenulations that lie at angles of as much as 30° to the original bedding.

Interbedded with some of the phyllite is a fine-grained gray quartzite, in part derived from chert. Lindgren (1894) called this rock "pthanite" and believed that it was formed, at least in part, by silicification of limestone. The general absence of stratification and granular texture suggests that this rock is not a metamorphosed sandstone.

Less abundant than phyllite and fine-grained quartzite are graphitic schistose quartzite containing some biotite and muscovite; quartz-biotite-(muscovite) schist, generally in contact aureoles; banded quartz-diopside-epidote-feldspar-tremolite rock, also in contact aureoles and probably a skarn; quartz-muscovite-chlorite-epidote rock, some of which contains a small amount of actinolite; tourmaline-bearing quartz-albite rock; and light-brown chert. Medium- to coarse-grained rocks such as metaconglomerate and metabreccia are rare. Crystalline limestone, in thin beds at several

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localities, is less pure than that in the two larger bodies east of Rattlesnake Bridge. Beds of metavolcanic rocks, chiefly metatuff, are common in the exposures near the northeastern corner of the area mapped.

Bands or layers of metasedimentary rocks differing in grain size and composition probably are either original beds or disrupted relics of original beds. Texture almost everywhere is xenoblastic, but some minerals, such as tourmaline, tend to be idioblastic.

METAVOLCANIC ROCKS

The most abundant rocks within the area mapped are those of volcanic origin. On the basis of the metamorphic facies defined by F. J. Turner (in Fyfe and others, 1958, p. 217–233), these rocks are grouped in two broad categories: (1) greenstone and greenschist, corresponding to the greenschist facies, and (2) amphibolite, corresponding chiefly to the almandine-amphibolite facies, but, in contact aureoles including also the hornblende hornfels and possibly the pyroxene hornfels facies.

GREENSTONE AND GREENSCHIST

Massive to schistose rocks characterized by the mineral assemblage albite-epidote-chlorite-(actinolite) are exposed near the northeastern corner of the mapped area. Typically these rocks are dense to fine grained (less than 0.02 to 0.1 mm) and light to medium green. In addition to the predominant albite, epidote, and chlorite, much of the greenstone and greenschist contains actinolite, quartz, zoisite or clinozoisite, calcite, leucoxene, sericite, stilpnomelane, and limonite. Locally, a few relict phenocrysts of plagioclase more calcic than albite remain as hosts for many small grains of epidote, quartz, calcite, and albite, which crystallized during later metamorphism. The texture in most of the greenstone and greenschist is felted or tufted; recrystallization has produced a dense aggregate of vaguely outlined grains. Actinolite is feathery, epidote is dusty to fine grained, and most of the other mineral grains are anhedral and very irregular.

The thicker bedded, more massive greenstone probably was derived from lava flows of mafic to intermediate composition; the thinner bedded, fissile greenschist appears to have been originally felsic to mafic tuff, although the fissility of some zones results from shearing along faults. Palimpsest features consist of rare phenocrysts and amygdules, largely replaced or filled with fine-grained metamorphic minerals. At many places the greenstone and greenschist are interbedded with metasedimentary rocks, chiefly phyllite and quartzite.

AMPHIBOLITE

Southwest of the exposures of greenstone and greenschist the metavolcanic rocks contain plagioclase more calcic than albite and were mapped as amphibolite (pl. 1). These rocks have a wide range in texture and composition, reflecting differences both in the original rocks and in the degree and kind of metamorphism. Most abundant are metamorphosed tuff beds and flows composed chiefly of blue-green hornblende or actinolitic hornblende, and plagioclase or epidote, or both (table 1). A few beds containing little or no hornblende but containing abundant plagioclase, quartz, sericite or muscovite, biotite, and calcite probably are derived from felsic tuff or tuffaceous sediments; these beds are not differentiated on the geologic map from the much more abundant amphibolite with which they are intercalated.

TABLE 1.—*Modes of amphibolite, in volume percent*

[Tr., trace. Location of samples shown on pl. 1]

Map unit	am_1	am_1	am_2	am_2	am_3	am_3	am_3	am_3	am_4	am_4
Sample	[1] 252	213	203	204	179	189	206	207	209	210
Amphibole	58	62.2	48.4	38.4	57.9	56.6	57.4	55.8	46.4	49.7
Plagioclase	22	17.7	39.6	28.5	35.7	39.8	33.8	36.5	0	0
Epidote or clinozoisite	11	4.6	7.2	24.6	.6	0	5.2	1.8	45.9	41.2
Quartz	.5	5.9	0	1.9	0	0	0	0	0	0
Augite	0	0	0	.1	0	0	0	0	.1	0
Sphene or leucoxene	2.5	4.6	0	1.3	2.4	3.1	2.9	5.4	0	0
Opaques	3	4.0	3.9	.1	2.0	.1	0	0	4.8	4.0
Apatite	Tr.	1.0	.9	.6	1.2	.3	.7	.5	.1	Tr.
Chlorite	2.5	0	0	Tr.	0	0	0	0	2.4	5.1
Muscovite or sericite	0	0	0	4.2	0	0	0	0	0	0
Calcite	.5	0	0	.3	0	0	0	0	0	0
An of plagioclase	18	12	25	([2])	44	42	55	47	----	----

[1] Modal values approximate.
[2] Groundmass, 38 percent; phenocrysts, 50 percent.

The amphibolite was subdivided in the field on the basis of overall differences in texture and composition into four mappable units (pl. 1). These units are exposed in four belts that trend northwest to north and are numbered consecutively from one to four from northeast to southwest. In places the contacts are gradational and do not precisely define a single stratigraphic horizon.

The first amphibolite unit is dense to fine grained (average grain size 0.05 to 0.2 mm) and is light green, except near contacts with the metagabbro and gabbro east of Pilot Hill and in phyllonitic zones, where it is nearly black. Massive zones, probably flows, alternate with thin-bedded schistose zones derived at least in part from tuff. The distinction between this unit and the greenstone and greenschist to the northeast is based on the anorthite content of the plagioclase, which is more than 10 percent in the amphibolite and less than 10 percent in the greenstone and greenschist.

The second amphibolite unit consists chiefly of light- to medium-green, dense to medium-grained (average grain size ranging from less than 0.1 to 0.4 mm), massive amphibolite derived from fairly thick flows of intermediate to mafic composition. Highly fissile chlorite schist occurs in the large fault zone adjacent to the long, narrow ultramafic body that includes Pilot Hill. Zones of porphyritic amphibolite in the eastern part of the belt that contain phenocrysts of somewhat altered plagioclase and uralitic hornblende were either porphyritic flows or shallow sills.

The third amphibolite unit grades from the second unit to the northeast and is bounded on the west by the north-trending fault zone marked by fissile chlorite schist east of the large ultramafic body of Flagstaff Hill. The rocks of the third unit are banded and layered, range in average grain size from about 0.1 to 1 mm, and are intercalated with irregular bands of metagabbro which are too thin to differentiate on the geologic map. The amphibolite is dark green or dark gray to nearly black and generally has a cleaner, more granoblastic texture than that of the other units. Some bands are uniform in thickness and sharply bounded, probably parallel with original bedding, but other bands have vague boundaries that are neither plane nor parallel.

The fourth amphibolite unit is more heterogeneous than the other three units, partly because its original rocks ranged from felsic tuff to mafic flows and partly because of large differences in degree of metamorphism. Except in parts of the contact aureole near the Rocklin pluton, where almost massive medium-grained amphibolite is conspicuous, rocks of the fourth unit are schistose and, in places, strongly lineated. The lineation is accentuated in porphyritic zones, where amygdules and original phenocrysts of pyroxene and plagioclase were first recrystallized to form uralitic amphibole, oligoclase or andesine, epidote, chlorite, and other minerals and then were smeared out into long, pencil-shaped aggregates.

Most of the amphibolite is derived from fairly mafic metavolcanic rocks and is typified by the assemblage amphibole-plagioclase-(epidote). The epidote may coexist with the plagioclase, may replace the plagioclase, or may be absent; all the plagioclase is more calcic than albite (An_{10}). The amphibole is blue-green hornblende or pale-green actinolitic hornblende rather than the actinolite characteristic of the greenschist. Actinolitic hornblende in somewhat ragged feathery prisms is associated with sodic oligoclase (average composition about An_{15}) or with epidote in the amphibolite of relatively low metamorphic grade in most of the first amphibolite unit and in parts of the fourth amphibolite unit. In the amphibolite of relatively high metamorphic grade in the third unit and part of the second, blue-green hornblende is associated with calcic oligoclase, andesine, or sodic labradorite, and the texture is granoblastic, with sharply outlined grains. The porphyritic rocks contain stubby phenocrysts of uralitic hornblende that in places grades inward into ragged relics of augite; the other phenocrysts consist of calcic andesine or sodic labradorite, altered in part to sericite and clinozoisite or epidote.

Chlorite is widespread in the amphibolite terrane but is not abundant, except in fissile schist of old fault zones, in layers of phyllonite, or on other slip surfaces. Sphene, replaced by small grains of leucoxene in the rocks of relatively low metamorphic grade, likewise is widely distributed, as are apatite, magnetite, and ilmenite. Quartz is present in some rocks, particularly those derived from tuff or tuffaceous sediments, which also contain muscovite (or sericite), calcite, biotite, clinozoisite (or epidote), and plagioclase. Pale-green diopside is associated with almandine garnet, hornblende, and plagioclase in mafic rocks of some contact aureoles, within a few meters of the contacts.

Modal analyses of 10 samples of amphibolite representing all four map units (table 1) indicate only a moderate range in composition. A greater range was apparent in a qualitative study of several times as many thin sections as those for which modes were measured. However, the modes probably are representative of the mafic flows that predominate in each of the four units.

Three of the modally analyzed samples also were analyzed chemically and compared with an analysis of olivine basalt from the Lassen Peak region (Clarke and Hillebrand, 1897), 120 miles to the north (table 2). The similarity of all four samples strongly suggests that the amphibolite was derived from basalt, an interpretation supported by structural, textural, and mineralogical evidence cited earlier.

ULTRAMAFIC AND MAFIC PLUTONIC ROCKS

The oldest plutonic rocks within the area are those ranging in composition from dunite to leucocratic gabbro. In general, these rocks are metamorphosed or are altered to varying degrees. Structural patterns, degree of metamorphism, and other evidence discussed later in this report suggest that most of the ultramafic and mafic plutonic rocks were intruded before the final episodes of folding and faulting that affected both these rocks and the enclosing metavolcanic and metasedimentary rocks. By contrast, the more felsic plutonic rocks of the Penryn and Rocklin plutons (see

TABLE 2.—*Chemical analyses of amphibolite and of olivine basalt from the Lassen Peak region*

[All values in weight percent. Location of samples shown on pl. 1. Olivine basalt analysis from Clarke and Hillebrand (1897, p. 200, sample L). Analyses of amphibolite samples, using rapid wet chemical methods, by Paul Elmore. Ivan Barlow, Samuel Botts, and Gillison Chloe]

Map unit	am_1	am_3	am_4	Olivine basalt
Sample	252	189	210	
SiO_2	46.5	50.4	48.3	47.93
Al_2O_3	16.2	14.9	18.9	18.51
Fe_2O_3	3.4	2.5	3.4	2.07
FeO	8.1	8.3	6.4	7.25
MgO	6.8	6.4	6.2	9.03
CaO	9.8	10.8	10.9	11.14
Na_2O	2.8	3.0	2.7	2.28
K_2O	.72	.18	.16	.24
H_2O	2.5	1.1	1.7	.76
TiO_2	1.9	1.6	.68	.73
P_2O_5	.24	.19	.02	.11
MnO	.20	.20	.18	.20
CO_2	<.05	<.05	<.05	0
Sum	99	100	100	100

"Quartz Dioritic Rocks") are largely unmetamorphosed and appear to have been intruded after the last major folding.

SERPENTINE AND PERIDOTITE

Most peridotite in the area is metamorphosed or is altered partly or entirely to serpentine, talcose rocks, siliceous rocks or magnesite; peridotite was mapped (pl. 1) only where its origin is revealed by relict grains and textures. Peridotite and its altered derivatives, which were mapped as serpentine or silicified serpentine, form (1) small sills and nearly concordant bodies, chiefly in the northeastern part of the area, (2) a long, narrow sill-like body that extends through Pilot Hill, (3) a large, irregular mass at Flagstaff Hill, and (4) a lenticular body along the western edge of the Pine Hill intrusive complex.

In the ultramafic body at Flagstaff Hill, the peridotite includes two main types mapped separately by Wells, Page, and James (1940): (1) dunite, originally consisting entirely or chiefly of olivine, and (2) lherzolite, originally containing both olivine and pyroxene. Both these types were also observed along the west side of the Pine Hill intrusive complex and at Pilot Hill, commonly as alternating layers. Chromite is abundant in the dunite or serpentine derived from dunite but not in the lherzolite or its derivatives. In addition to the dunite and lherzolite, locally occurring relics of enstatite suggest the presence of altered saxonite.

The rocks mapped as serpentine consist chiefly of light- to dark-green aggregates of antigorite, chrysotile, and, commonly, some chlorite; talc schist occurs in highly sheared zones, and magnesite is found locally near Flagstaff Hill. Thinly layered serpentine, talc schist, chlorite schist, and actinolite schist probably are layered complexes of peridotite and gabbro or peridotite and metavolcanic rocks; these were mapped as serpentine and amphibolite (pl. 1). Probable hydrothermal alteration has produced silicified zones in the serpentine, in which the serpentine and, in some cases, peridotite or pyroxenite are wholly or partly replaced by brown jasper. Only the more extensive silicified zones are shown on the geologic map (pl. 1).

PYROXENITE AND METAPYROXENITE

Pyroxenite, some of which is sheared or hydrothermally altered, forms many small sills and nearly concordant bodies in the western part of the metamorphic terrane and also constitutes parts of the ultramafic body at Flagstaff Hill and the Pine Hill intrusive complex.

Small sills of metapyroxenite and sheared zones of similar rock in the larger masses of pyroxenite are characterized by schistose rocks containing rounded grains of clinopyroxene—probably diopsidic augite—replaced wholly or in part by actinolite, in a matrix of very fine grained chlorite, talc, and actinolite or tremolite. All stages of deformation and alteration have been observed ranging from almost massive unsheared pyroxenite to fissile chlorite-tremolite-talc schist.

Except for the rocks just described, the pyroxenite generally is less extensively altered than the peridotite and is relatively resistant to erosion, forming large bold outcrops. In the Pine Hill intrusive complex, the pyroxenite tends to form ridges above adjacent exposures of somewhat less resistant gabbro. The pyroxenite of the larger masses characteristically is only slightly foliated, very coarse to medium grained, dark green where fresh, and black, rough, and hackly on weathered surfaces where parting planes of the pyroxene are prominent. In thin section, this rock is identified as a clinopyroxenite composed largely of pale-gray diopsidic augite (diallage) having prominent pinacoidal parting and much less prominent prismatic cleavage along which a pale-green amphibole has formed as an alteration product. Rounded and cracked grains of magnesian olivine altered in part to chrysotile are present in amounts ranging from 5 to 20 percent. Other constituents include small amounts of magnetite or ilmenite, hematite, and chlorite.

GABBRO AND METAGABBRO

Gabbroic intrusive rocks, commonly thermally or dynamothermally metamorphosed, are widespread in the metamorphic terrane. Relatively unmetamorphosed gabbro is present in the larger intrusive bodies—the Pine Hill intrusive complex and, locally, the mafic intrusive body east of Pilot Hill. However, most of the smaller sills are composed of metagabbro that reflects to a considerable degree the intensity and kind of metamorphism undergone by the adjacent finer grained metamorphic rocks.

The metagabbro varies greatly in composition and texture from place to place, although evidence of at least some shearing and recrystallization is almost universal. The sills intruding the greenstone, greenschist, and metasedimentary rocks near the northeastern corner of the area consist of actinolite or tremolite, albite, clinozoisite, and commonly chlorite and leucoxene. Some of the actinolite surrounds relics of augite. Farther southwest, sodic oligoclase takes the place of the albite, and, in much of the large body near Pilot Hill, blue-green hornblende takes the place of the actinolite or tremolite. The hornblende and oligoclase are relatively free of small inclusions or sieve structure and have more distinct grain boundaries than most of the actinolite and albite. Recrystallization is more complete in the hornblende-oligoclase rock than in the actinolite-albite rock, and none of the original grains remain in the former.

The relatively unaltered gabbro of most of the Pine Hill intrusive complex and small parts of the mafic body near Pilot Hill is medium to coarse grained, light to dark gray, allotriomorphic granular to locally ophitic, and consists chiefly of plagioclase and clinopyroxene in variable proportions. Some of the gabbro is almost massive, but most is moderately to clearly layered.

Plagioclase in four samples of gabbro from the Pine Hill intrusive complex has an average anorthite content in the range of 65 to 85 percent; Emerson (1969), in a study of many more samples from the entire body, reports a greater range in composition, from An_{45} to An_{95}. Compositional zoning is not prominent; most grains have a range in anorthite content of 10 percent or less.

Most of the pyroxene in the gabbro is clinopyroxene, probably augite in the classification of Hess (1941, p. 515, 573), and is not greatly different from that in the pyroxenite. Hypersthene was observed in one sample of leucocratic gabbro, where it rims a few olivine grains and forms irregular exsolution lamellae in the augite. Olivine is common in gabbro of the Pine Hill intrusive complex but rare in gabbro near Pilot Hill. Most of it forms rounded, corroded grains, altered in cracks to iddingsite.

PINE HILL INTRUSIVE COMPLEX

The Pine Hill intrusive complex, described as the Pine Hill layered gabbro complex by Emerson (1969) and Springer (1969), is an informal name given to an elliptical body about 11 miles long in a north-northwest direction and 5 miles wide; only its northern end is within the area of the geologic map (pl. 1). The unusual features of the complex are its very mafic average composition, its heterogeneity, its small to larger scale layering or banding, and its concentric large-scale layering.

The rocks of the complex range from serpentinized dunite to leucocratic gabbro; pegmatite and aplite dikes of granodioritic composition are abundant locally near the outer margins of the body. Most of the serpentine and peridotite are along the western margin. The rest of the complex within the mapped area consists chiefly of layered pyroxenite and gabbro. Individual layers commonly are lenticular and range in width from a few millimeters to more than 300 meters. The layering is concentric, dips steeply to vertically, and is parallel to the margins of the body. Layers thick or wide enough to show at the scale of the geologic map (pl. 1) are designated separately as pyroxenite (mafic minerals more than 90 percent) or gabbro (mafic minerals less than 90 percent). Strongly banded rock having distinct layers of pyroxenite and gabbro too thin or poorly exposed to show on the geologic map are shown as pyroxenite and gabbro (fig. 2).

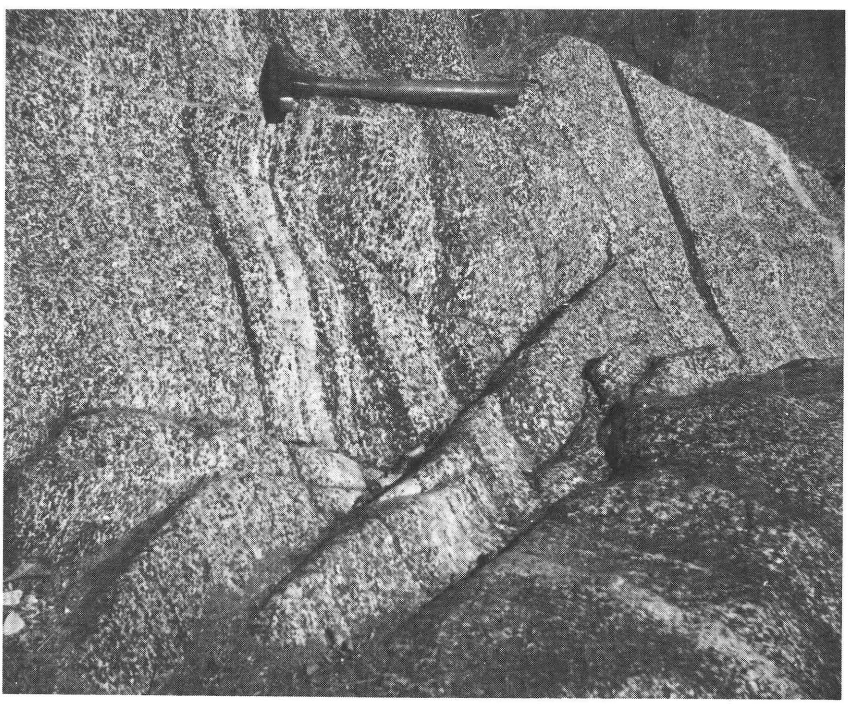


FIGURE 2.—Thinly layered gabbro and pyroxenite in Pine Hill intrusive complex. Dark layers are chiefly large anhedral grains of clinopyroxene and a small amount of interstitial olivine. Light bands consist almost entirely of calcic labradorite.

The layered or banded structure and local cross-layering similar to crossbedding in sediments suggest rhythmic gravitational settling. Springer (1969) suggested that the complex was intruded as a nearly horizontal thick sill or series of sills and was later folded into its present concentric pattern. According to this hypothesis, the pyroxenite layers represent early-formed crystals that settled by gravity as the magma—or, more likely, a crystal mush—was injected almost horizontally, and the lenticular septum of amphibolite in the northern part of the body represents a remnant of the country rock. Emerson (1969) found that the plagioclase in each successive layer of gabbro becomes progressively more calcic, and therefore denser, toward the center of the complex, which would also be toward the bottoms of the layers if they were originally intruded horizontally and were subsequently tilted and folded to their present configuration.

QUARTZ DIORITIC ROCKS

Quartz dioritic rocks form two plutons, parts of which occupy the western two-thirds of the mapped area, and a much smaller body farther east at Oregon Bar (pl. 1). The two western plutons were mapped by Lindgren (1894) as a single body of granodiorite enclosing two small masses of gabbrodiorite in its eastern part.

Curtis, Evernden, and Lipson (1958, p. 6, 10, 12) presented evidence, both from potassium-argon age determinations of two samples and from field relations, that the body mapped by Lindgren (1894) as granodiorite comprises at least two separate major intrusive bodies. They applied the name "Rocklin Granodiorite" to the younger, southern body and the name "Horseshoe Bar Quartz Diorite" to the older, northern body, typified by a dark rock exposed west of Horseshoe Bar on the North Fork of the American River.

The present study confirms the general interpretation of Curtis, Evernden, and Lipson (1958) that Lindgren's (1894) single mass consists of two separate plutons. The younger is herein called the Rocklin pluton from the town where it is well exposed in building-stone quarries. The Rocklin pluton, composed almost entirely of trondhjemite (silicic quartz diorite), corresponds to all or part of the Rocklin Granodiorite of Curtis, Evernden, and Lipson (1958) and occupies the southern third of the granodiorite body of Lindgren (1894). The second pluton, composed of calcic to intermediate quartz diorite, includes the Horseshoe Bar Quartz Diorite of Curtis, Evernden, and Lipson (1958) but also includes a lighter colored rock to the west and is herein called the Penryn pluton from the small town near which the rock is exposed in quarries.

The quartz diorite at Oregon Bar is considerably more sheared and hydrothermally altered than the Penryn and Rocklin plutons and is therefore inferred to be older than those plutons. However, movement on faults responsible for the shearing and alteration may have continued after the emplacement of the Penryn and Rocklin plutons, so that the greater apparent age of the Oregon Bar body may not be real.

QUARTZ DIORITE AT OREGON BAR

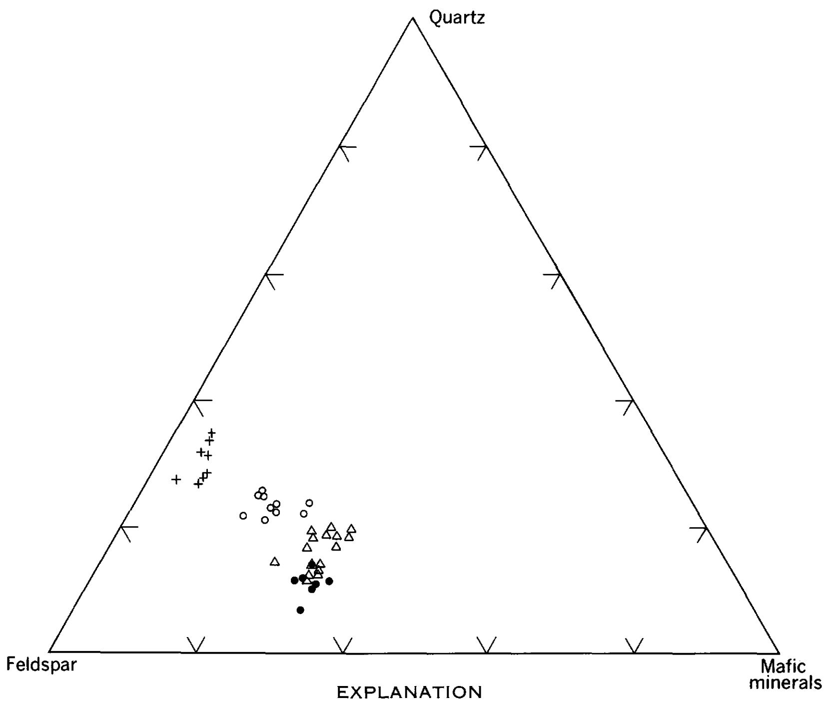
The quartz diorite extending northward from Oregon Bar on the North Fork of the American River is light gray, weathers to pale yellow, and has a cataclastic texture in which the ferromagnesian minerals form thin, discontinuous streaks around lenticular grains of plagioclase or form irregular interstitial patches. The ferromagnesian minerals are largely altered to chlorite and epidote, and most of the plagioclase is altered to sericite and epidote. Granulated quartz occurs as anastomosing veinlets and irregular groups. Where well exposed in the river channel, contacts of the quartz diorite and the metamorphic rocks are sharp, and little contact effect is evident. The internal deformation of the quartz diorite probably resulted from movement on the large fault a short distance to the west.

PENRYN PLUTON

The Penryn pluton occupies the western part of the mapped area and is bounded on the east and north by preplutonic metamorphic rocks and on the southwest by the younger Rocklin pluton. The Penryn pluton is composed chiefly of medium- to coarse-grained quartz diorite, in which the most abundant constituents are plagioclase (calcic andesine to calcic oligioclase), quartz, hornblende, and biotite. Fine-grained dark inclusions and light and dark schlieren are conspicuous locally but make up less than 10 percent of the total volume of the pluton. Dikes, mostly leucocratic, are small and sparse except near contacts with the Rocklin pluton, where they appear to be offshoots of that younger body.

On the basis of modal differences, structure, and texture, three distinctive phases of the quartz diorite of the Penryn pluton are recognized: (1) a dark-colored phase, in the eastern part of the pluton, (2) a medium-colored phase, surrounding the dark-colored phase and occupying the marginal part of the pluton, and (3) a light-colored phase, lying west of the medium-colored phase, in the central part of the pluton (pl. 1). The dark-colored phase corresponds to the Horseshoe Bar Quartz Diorite of Curtis, Evernden, and Lipson (1958). Boundaries of all three phases are gradational at most places.

Modal analyses of 44 thin sections from 28 samples, and of 5 stained slabs, corroborated by megascopic examinations at many additional sites, indicate that each of the three phases is fairly homogeneous and different in composition from the other phases (fig. 3 and table 3). Modal quartz ranges from only about 10 percent in the dark-colored phase to about 25 percent in the light-colored phase. Plagioclase, the predominant constituent, does not vary systematically in amount from place to place, but the anorthite content decreases from 45 percent in some of the dark-colored phase to 25 percent in parts of the light-colored phase. Potassium feldspar is absent in the dark-colored phase and is present only locally in minor amounts in the other two phases. Relative amounts of hornblende and biotite are highly variable in the medium-colored and light-colored phases; only in the dark-col-



EXPLANATION

+ Rocklin pluton

○ Light-colored phase of Penryn pluton

△ Medium-colored phase of Penryn pluton

● Dark-colored phase of Penryn pluton

FIGURE 3.—Modal composition of samples from the Penryn and Rocklin plutons.

ored phase is hornblende consistently more abundant than biotite. Relics of both hypersthene and augite are present in the dark-colored phase, only a few grains of augite remain in some of the medium-colored phase, and no pyroxene at all was observed in the light-colored phase. The color index (total mafic constituents), which tends to vary inversely with quartz content, averages nearly 30 percent in the dark-colored and medium-colored phases but averages only about 19 percent in the light-colored phase.

Quartz is chiefly interstitial and perhaps was the last mineral to crystallize, except possibly in part of the light-colored phase, where it forms large groups of rounded grains which are conspicuous on weathered surfaces. Most quartz grains are at least slightly fractured and, particularly in the medium-colored and dark-colored phases, show strain by patchy or undulatory extinction, or by a small 2V. In the more severely deformed zones of the medium-colored phase the quartz forms long, irregular stringers of very small grains.

Among the major constituents in all three phases, plagioclase ordinarily has the most nearly euhedral development. Most of the plagioclase grains are zoned; progressive and oscillatory zoning commonly are observed in the same thin section. Zoning and multiple twinning are somewhat incompatible, although many grains have both. Strain, indicated by bent twin lamellae, is common, particularly in the medium-colored phase. Many other grains are granulated. Almost all the plagioclase is clouded to variable degrees by alteration. The more calcic zones are altered extensively to very fine grained sericite, zoisite, clinozoisite, epidote, clay minerals, or calcite. Much of the plagioclase contains very small inclusions of hornblende, biotite, quartz, apatite, and opaque minerals.

Hornblende forms nearly euhedral prisms in parts of the Penryn pluton but is more commonly subhedral to anhedral. As many as three types of hornblende are present in the dark-colored and medium-colored phases, where much of the hornblende has replaced pyroxene entirely or in part.

Biotite forms anhedral grains or groups of grains, many of which are intergrown with or molded on hornblende grains. The biotite typically is embayed, extremely ragged, or skeletal, and contains inclusions of plagioclase, quartz, apatite, sphene, opaque minerals, and, locally, very small grains of zircon. Most of the biotite is pleochroic in pale yellow and brown; an intergrown green variety may represent incipient alteration to chlorite. The coarsest biotite occurs in the light-colored phase, where some of the flakes and groups of flakes as much as 10 mm (millimeters)

TABLE 3.—*Modes of the Penryn pluton*

[Kind of sample: TS, thin section; SS, stained slab; number in parentheses is number of thin sections. Plagioclase includes alteration products. Color index includes accessories. Location of samples shown on pl. 1]

Sample No.	Kind of sample	Quartz	K-feldspar	Plagioclase	Biotite	Hornblende	Augite	Hypersthene	Accessories	Color index	Percentage of An in plagiocase
DARK-COLORED PHASE											
1	TS(2)	13.6	0	57.6	8.2	19.3	0.7	0.3	0.3	28.8	30–35
2	TS(2)	11.6	0	59.7	9.3	12.4	1.5	5.1	.4	28.7	40–45
3	TS(3)	10.8	0	58.6	9.5	16.4	.5	3.8	.4	30.6	35–40
4	TS	10.3	0	59.0	9.5	12.4	1.4	6.6	.7	30.7	50
5	TS	11.4	0	56.1	7.6	22.0	.3	1.8	.7	32.5	35
6	TS	7.1	0	61.9	5.6	21.1	.7	2.6	1.0	31.0	40–45
7	TS	11.6	0	60.4	8.7	14.9	1.1	2.9	.4	28.0	----------
Average	----------	10.9	0	59.0	8.3	16.9	.9	3.3	.6	30.1	40
Standard deviation	----------	2.0	----------	1.9	1.4	4.0	.5	2.1	.2	1.6	----------
MEDIUM-COLORED PHASE											
8A [1]	TS(4)	12.7	0	56.2	10.1	19.9	0.6	0	0.5	31.1	35
8B [1]	SS	13.8	0	56.3	----------	----------	----------	----------	----------	29.9	----------
9	TS(4)	16.8	0	52.2	15.5	15.0	.2	0	.3	31.0	35
10	TS(4)	16.8	0	55.8	12.3	14.7	0	0	.4	27.4	35–40
11	TS	12.7	0	57.8	14.7	14.8	0	0	.2	29.5	35–40
12	TS	18.5	0	54.3	17.1	9.9	0	0	.2	27.2	35
13	TS	13.3	0	56.1	13.3	16.8	0	0	.4	30.6	30–35

14	TS	18.3	0	51.4	11.9	18.1	<0.1	0	.4	30.3	40
15	TS	11.9	0	59.2	8.7	19.2	.4	0	.5	28.9	40
16	TS	19.9	0	48.4	16.4	15.4	0	0	.2	31.7	30–35
17	TS	14.1	0	62.0	7.3	15.6	.7	0	.1	23.9	35–40
18	TS	18.5	0	52.7	15.3	13.2	<0.1	0	.3	28.8	35–40
19	TS(2)	19.4	0	53.7	13.7	13.2	<0.1	0	.2	26.9	----------
20	TS	17.9	0	49.8	16.1	15.5	0	0	.6	32.3	----------
21	TS(2)	12.2	0	58.3	8.1	20.5	.3	0	.6	29.5	----------
22	TS	19.2	2.1	51.1	13.0	16.6	.1	0	.5	29.7	----------
Average	----------	15.8	.1	54.7	12.9	15.9	.2	0	.4	29.4	35–40
Standard deviation	----------	3.0	.1	3.7	3.1	2.8	.1	----------	.1	2.2	----------
LIGHT-COLORED PHASE											
23	SS	21.7	0.7	61.7	----------	----------	----------	----------	----------	15.9	25
24	SS	23.6	1.2	56.1	----------	----------	----------	----------	----------	19.1	30–35
25	SS	23.3	.4	57.4	----------	----------	----------	----------	----------	18.9	----------
26	TS	26.0	1.2	56.8	8.2	7.8	0	0	<0.1	16.0	30
27	SS	25.8	.2	58.1	----------	----------	----------	----------	----------	15.9	----------
28	TS	24.8	0	59.1	10.0	6.1	0	0	.2	16.3	30–35
29	TS(2)	21.1	1.0	60.0	4.2	13.7	0	0	.2	18.1	30–35
30	TS	24.0	.7	51.6	13.1	10.2	0	0	.4	23.7	35
31	TS	22.1	.4	58.2	9.2	10.1	0	0	.9	20.2	25–30
32	TS	22.3	1.4	52.5	14.9	8.9	0	0	.1	23.9	35
Average	----------	23.5	.7	57.2	9.9	9.5	0	0	.4	18.8	30
Standard deviation	----------	1.7	.5	3.3	3.8	2.6	----------	----------	.3	3.0	----------

[1] Samples 8A and 8B are from the same outcrop.

across give this phase of the pluton much of its distinctive spotted or dappled character (fig. 4).

Some of the quartz diorite, particularly the light-colored phase, is almost massive, but almost everywhere a foliation is defined by crude parallelism of the (010) faces of the plagioclase, by a tendency toward planar orientation of biotite flakes and hornblende prisms, and by vaguely bounded light and dark schlieren. Cataclastic or protoclastic texture is characteristic of some zones in the medium-colored phase. In some of that phase, augen structure, in which shredded biotite and broken small grains of hornblende, quartz, and plagioclase partly surround augen of plagioclase as much as 10 mm long, is slightly to moderately developed. In the southeastern part of the exposures of the medium-colored phase, spindle-shaped aggregates of shredded biotite and c axes of hornblende prisms define a moderately strong lineation.

Dark fine-grained inclusions are conspicuous in parts of the medium-colored and light-colored phases; these occur in a variety of shapes and sizes up to about 50 cm (centimeters) in length (fig. 4). Some inclusions appear to be irregular triaxial ellipsoids,

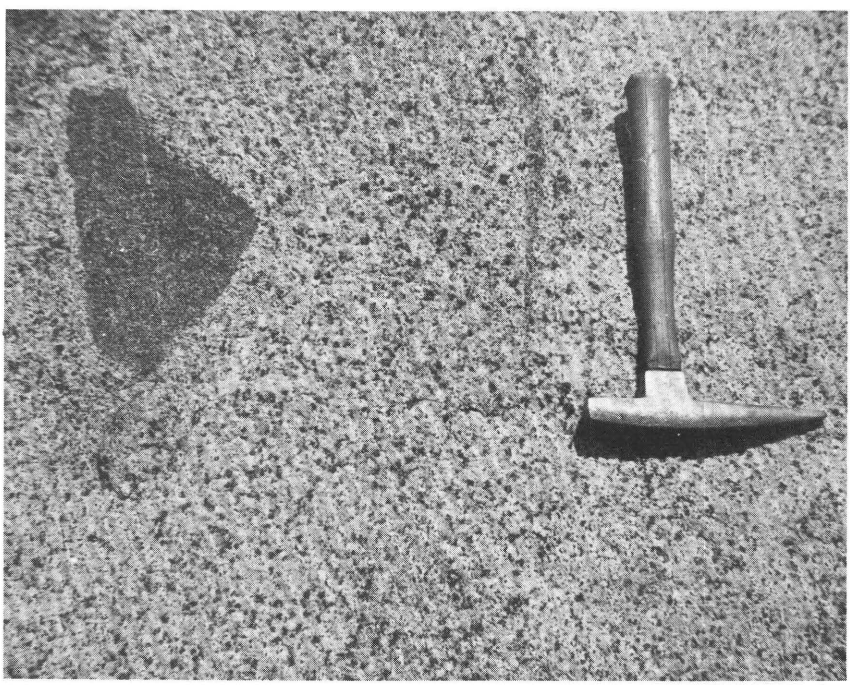


FIGURE 4.—Light-colored phase of Penryn pluton about one-half mile northwest of Loomis. Typical dappled appearance is given by large biotite flakes. Crude foliation parallel to pick handle is defined by wispy schlieren and long dimension of dark inclusion at left. Inclusion is surrounded by a zone about 20 mm thick which is somewhat finer grained than remainder of host.

some are flat disks, and some are long and spindle-shaped. Many have a random orientation, but the minor axis in most of the ellipsoidal and discoidal inclusions is perpendicular to the foliation of the host.

Vaguely defined light and dark schlieren and small lenticular clots of hornblende and biotite are even more widespread than the inclusions (fig. 4), although at no place do they constitute more than 10 percent of the total volume. No definite increase in the size or number of inclusions or schlieren toward the margins of the pluton was observed.

The Penryn pluton apparently was emplaced forcefully in a terrane of steeply dipping metamorphic rocks, judging by the manner in which the schistosity and bedding of the metamorphic rocks are deflected around the pluton. Primary foliation is parallel to the margins of the pluton and is also parallel or nearly parallel to the schistosity and bedding in the adjacent metamorphic rocks. The fairly strong lineation in the southeastern part of the pluton plunges about 55° to 75° northeastward, parallel to the lineation in the amphibolite to the east. This lineation may have resulted in part from deformation accompanying the emplacement of the Rocklin pluton, after the Penryn pluton was virtually solid. The eastern, outer part of the Penryn pluton—the medium- and dark-colored phases—probably ascended as a viscous, semicrystalline mush, but the western, interior part—the light-colored phase—probably crystallized somewhat later and may have been more completely liquid at the time of emplacement. Although the Penryn pluton is roughly concordant, projection or regional trends of foliation and bedding of the amphibolite across the contact suggests that sizable volumes of amphibolite may be missing southeast of the Penryn pluton. This relation suggests stoping and partial assimilation of the missing fragments of amphibolite. Such a process might account in part for the relatively mafic character of the medium- and dark-colored phases of the outer part of the pluton.

ROCKLIN PLUTON

The Rocklin pluton is exposed in the southwestern corner of the mapped area, and it extends farther to the south and west where it is covered by Cenozoic deposits of the eastern Sacramento Valley. Unlike the somewhat older Penryn pluton to the north, the Rocklin pluton is largely nonfoliated or very weakly foliated. The poorly exposed contact of the two plutons is marked by a swarm of light-colored dikes, tongues, and small apophyses, many of which are offshoots of the Rocklin pluton. Zones of faintly to moderately banded rock that appears to be a hybrid formed by partial assimilation of the Penryn pluton by the Rocklin pluton observed at several places in the contact zone.

Most of the Rocklin pluton consists of light-gray hypidiomorphic granular trondhjemite (silicic quartz diorite) which differs from the quartz diorite of the Penryn pluton in having smaller average grain size, lighter color, and less biotite in smaller, more evenly distributed grains. Hornblende is scarce or absent, although small amounts of it occur in a more mafic phase at Folsom Dam, 4 miles south of the mapped area (Kiersch and Treasher, 1955). Quartz is more abundant and conspicuous than in most of the Penryn pluton. In addition to the interstitial quartz, rounded grains occur in large clusters as much as 15 mm in diameter, which stand out prominently where the trondhjemite is weathered, giving it a very rough, coarse surface.

Most of the plagioclase grains are stubby and rectangular. Polysynthetic twinning is not conspicuous in the plagioclase, which has an average anorthite content of about 20 to 25 percent. Myrmekitic intergrowth of fine rodlike quartz in an albite host occurs at boundaries between the plagioclase and interstitial soda microcline or anorthoclase.

The average modal composition of the Rocklin pluton within the area mapped, on the basis of eight samples is shown in table 4.

In general, the pluton is somewhat finer grained and more leucocratic in the western part of the exposed area, in the vicinity of Rocklin, than it is to the east and southeast. In the southeastern part of the pluton within the mapped area the average grain size approaches 4 mm, as compared with 2–3 mm elsewhere, and biotite flakes are nearly as large as some in the light-colored phase of the Penryn pluton.

Most of the trondhjemite of the Rocklin pluton is slightly to moderately altered; even in the fresh-looking rock exposed in

TABLE 4.—*Modes of the Rocklin pluton*

[Kind of sample: TS, thin section; SS, stained slab. Plagioclase in stained slabs includes alteration products and muscovite. Location of samples shown on pl. 1]

Sample No.	Kind of sample	Quartz	K-Na feldspar	Plagioclase	Muscovite	Biotite	Accessories	Color index	Percentage of An in plagioclase
33	TS	31.5	5.4	56.8	1.5	3.2	1.6	4.8	------
34	SS	26.9	6.5	62.8	------	------	------	3.8	20
35	SS	34.7	6.6	54.0	------	------	------	4.7	------
36	SS	33.4	5.4	56.1	------	------	------	5.1	20–25
37	SS	31.2	4.6	58.1	------	------	------	6.1	------
38	SS	27.4	1.0	64.0	------	------	------	7.6	------
39	TS	28.0	1.4	62.9	.2	6.8	.7	7.5	------
40	SS	26.6	6.5	59.9	------	------	------	7.0	------
Average	-----	30.0	4.7	59.3	------	------	------	5.8	------
Standard deviation	-----	3.2	2.3	3.7	------	------	------	1.4	------

quarries, biotite is altered in part to chlorite and epidote, and plagioclase is altered slightly to sericite, epidote, calcite, and a clay mineral.

In contrast to the Penryn pluton, schlieren and dark-colored inclusions are scarce in the Rocklin pluton. Vaguely defined patches containing somewhat more abundant biotite than the average were observed at a few localities but make up an insignificant total volume. Quartz veins and dikes of aplite, pegmatite, and alaskite likewise are scarce, except in the border zones near the Penryn pluton to the north and the metamorphic rocks to the east.

The emplacement of the Rocklin pluton seems to have been more passive than that of the Penryn pluton, and it probably was intruded as a largely liquid magma after the Penryn pluton was virtually solid. Many dikes of pegmatite, aplite, and alaskite were intruded into the fractured margins of both plutons during the late stages of the magmatic activity. Very late hydrothermal activity is represented by the locally abundant quartz veins.

AGE

The age of the Penryn and Rocklin plutons is indicated by both radiometric age dating and stratigraphic evidence. Curtis, Evernden, and Lipson (1958, p. 6) report potassium-argon ages of 131.5 and 130.6 million years (m.y.), respectively, for biotite and muscovite in a sample of "biotite-muscovite-hornblende quartz diorite" from a large quarry in Rocklin. This rock clearly is trondhjemite of the Rocklin pluton. Curtis and his coworkers also dated biotite in their Horseshoe Bar Quartz Diorite from a quarry 3 miles southeast of Loomis as 142.9 m.y.; this sample represents the dark-colored phase of the Penryn pluton. Somewhat later, Evernden and others (1961, p. 82, 86) redetermined the age of biotite in their Horseshoe Bar Quartz Diorite, again by the potassium-argon method, as 136 m.y.

The age of the Penryn and Rocklin plutons also is indicated by the following stratigraphic evidence. At Folsom, 4 miles south of the Auburn quadrangle, the Rocklin pluton is reported to intrude the Mariposa Formation (Lindgren, 1894; Curtis and others, 1958, p. 6) and is overlain unconformably by gently tilted siltstone and sandstone containing marine fossils assigned to the Campanian Stage of the Upper Cretaceous by Popenoe, Imlay, and Murphy (1960, p. 1526). According to Taliaferro (1942), the Mariposa Formation represents the Oxfordian and Kimmeridgian Stages of the Upper Jurrassic. Lindgren (1894) shows his granodiorite as intruding contact-metamorphosed rocks of the Mariposa Formation along the northern border of the intrusion, as well as at Folsom. The "granodiorite" along the northern border, which is several miles north of the present mapped area, probably is part of the Penryn pluton. Therefore, the Penryn pluton, as well as the Rocklin pluton, is younger than the Mariposa Formation, and both plutons are post-early Kimmeridgian and pre-Campanian.

Thus, the stratigraphic evidence corroborates the radiometric evidence, which indicates that the Penryn and Rocklin plutons were emplaced about at the end of the Jurassic or at the beginning of the Cretaceous Period, according to the radioactive time scales of Holmes (1960) and Kulp (1961). The potassium-argon dates also corroborate the sequence of emplacement that is clearly revealed by the contact and structural relations of the two plutons, although the indicated difference in ages is within the possible error in the determinations.

CHEMICAL COMPOSITION

Chemical analyses of two samples from the Penryn pluton and one sample from the Rocklin pluton are given in table 5. Sample 8C represents the medium-colored phase of the Penryn pluton, sample 24B represents the light-colored phase of the same pluton, and sample 35 represents the Rocklin pluton. Each of the three samples has close to the average modal composition for that pluton or phase of the pluton (see tables 3 and 4), and the chemical compositions therefore are believed to be fairly representative.

The analyses indicate a substantial increase in silica content from 61.5 percent in the fairly calcic quartz diorite of the medium-colored phase of the Penryn pluton to 73.6 percent in the highly silicic quartz diorite (trondhjemite) of the Rocklin pluton. The analysis of the light-colored phase of the Penryn pluton occupies a position about half way between the other two analyses,

TABLE 5.—*Chemical analyses of three samples from the Penryn and Rocklin plutons*

[Analyses, using rapid wet chemical methods, by Paul Elmore, Ivan Barlow, Samuel Botts, and Gillison Chloe. Location of samples shown on pl. 1]

Constituent	Sample No.		
	8C	24B	35
SiO_2	61.5	67.5	73.6
Al_2O_3	16.2	15.9	15.4
Fe_2O_3	1.2	1.3	.61
FeO	3.9	1.8	.58
MgO	4.4	2.1	.39
CaO	6.8	5.2	2.6
Na_2O	3.8	4.3	4.8
K_2O	.64	.78	1.4
H_2O	.66	.64	.40
TiO_2	.52	.32	.18
P_2O_5	.21	.18	.10
MnO	.11	.08	.03
CO_2	<.05	<.05	<.05
Sum	100	100	100

not only in silica content, but in the content of the other oxides as well. In general, as silica increases, the oxides of sodium and potassium increase, and the oxides of iron, magnesium, calcium, titanium, phosphorus, and manganese decrease—the usual variation in similar suites of plutonic rocks. The significant characteritic of all these rocks, suggested also by the modal analyses, is the high ratio of sodium to potassium, even in the highly silicic trondhjemite of the Rocklin pluton.

DIKE ROCKS

MAFIC DIKES

Mafic dikes ranging in width from a few centimeters to several meters are fairly common in parts of the metamorphic terrane and in the Pine Hill intrusive complex but are rare in the Penryn and Rocklin plutons. Most of the dikes cutting the metamorphic rocks consist of much-altered porphyritic diabase. This rock is light to dark green and contains scattered small phenocrysts of plagioclase and amphibole (after pyroxene) in a fine-grained to dense groundmass of chlorite, epidote, and plagioclase. In parts of the ultramafic body at Flagstaff Hill the dikes of altered diabase have been strongly sheared to form chloritic and talcose schist. In the Pine Hill intrusive complex, mafic to ultramafic dikes and irregular discordant bodies consist of diorite, diabase, quartz diorite, gabbro, and pyroxenite. Bodies more than 30 meters wide were observed in places, but most masses are considerably smaller. Porphyritic and seriate textures are common in the gabbro and diabase, and in some dikes in the Pine Hill intrusive complex, phenocrysts of augite or hornblende after augite reach 50 mm in length. In the southeastern part of the Penryn pluton, an elongate lenticular body of pegmatitic diorite or gabbro consists mostly of stubby euhedral prisms of hornblende averaging about 20 mm in length and a small amount of interstitial plagioclase.

LEUCOCRATIC DIKES

The most numerous dikes are those composed of pegmatite, aplite, and alaskite. These leucocratic dikes are especially abundant in the broad contact zone between the Rocklin and Penryn plutons, in the marginal part of the Pine Hill intrusive complex, and in the metamorphic terrane northwest of the Pine Hill intrusive complex. Smaller numbers of leucocratic dikes are scattered sporadically throughout the rest of the Rocklin and Penryn plutons and the Pine Hill intrusive complex.

The pegmatite, aplite, and alaskite consist of very coarse grained to fine-grained albite, microcline, quartz, and, commonly, small amounts of muscovite, biotite, chlorite, and epidote. The modal composition of most leucocratic dikes ranges from trondhjemite (silicic quartz diorite) to granite; quartz monzonite probably is predominant. The five samples in table 6 illustrate a representative range in composition.

Some of the pegmatite has a hypidiomorphic granular texture, but many of the sills and dikes of pegmatite and alaskite intruding the third amphibolite unit northwest of the Pine Hill intrusive complex are moderately to strongly sheared and granulated. Most other leucocratic dikes are allotriomorphic granular in texture.

STRUCTURE

FAULTS

Faults in the area range from small fractures or shears on which displacements may be measured in millimeters or centimeters to large zones of highly schistose, mylonitic rocks in which the aggregate displacements are unknown but may amount to several kilometers.

The very small faults, which include slip cleavages of microscopic scale, are too numerous to be shown on the geologic map (pl. 1). The aggregate displacement on hundreds and thousands of these features may be large, however; the wide zones of sheared, mylonitic rock are in part a dense assemblage of small slips. Almost all the very small faults or slip cleavages record predominantly strike-slip movements, assuming that the nearly vertical associated lineations are parallel to the *b* tectonic axis.

The faults portrayed by single lines on the geologic map (pl. 1) are intermediate in size between the small fractures and large fault zones and consist of single planes or narrow zones. The actual fault planes, which commonly are marked by slickensides or gouge, cannot be observed directly except in the good exposures along the American River and its canyon walls and along some of the tributaries. The locations of such faults are indicated by lines of offset contacts, juxtaposition of different units, and alinement of ravines and saddles. Where the evidence for these faults is vague and mainly topographic, they are queried on the map. Fault planes dip steeply at most places. Slickensides on several surfaces indicate normal faulting, but in some faults the movement has been largely lateral.

TABLE 6.—*Modes of leucocratic dikes*

[Kind of sample: TS, thin section; SS, stained slab. Plagioclase in stained slabs includes alteration products and muscovite. Location of samples shown on pl. 1]

Sample No.	Rock type	Kind of sample	Quartz	Microcline	Plagioclase	Muscovite	Biotite	Accessories	Color index	Percentage of An in plagioclase
41	Alaskite	SS	32.1	0.4	60.8	------	------	------	6.7	---------
42	Pegmatite	SS	29.1	54.4	16.3	------	------	------	.2	---------
43	Alaskite	TS	32.3	10.2	44.8	8.0	4.3	0.4	4.7	---------
44	do	SS	27.2	27.5	44.7	------	------	------	.6	---------
45	Aplite	TS	31.4	26.7	40.5	.7	.2	.5	.7	5

Most of the major faults, which cannot be shown by single lines on the geologic map (pl. 1), are characterized by zones of highly fissile chlorite schist as much as several hundred meters wide, although the usual width is a few meters or a few tens of meters. At many places, thin branching zones of phyllonite enclose lensoid prisms of relatively massive unsheared rock. These large fault zones are difficult to distinguish from zones of schistose rock produced by processes unrelated to faulting.

Clark (1960, pl. 1) shows two branches of the Bear Mountains fault zone of his Foothills fault system within the area of the south half of the Auburn quadrangle. He shows the western branch as following the western margin of the Pine Hill intrusive complex south of the Auburn quadrangle, then as crossing the metamorphic rocks (amphibolite) between the Pine Hill intrusive complex and the ultramafic mass at Flagstaff Hill. The fault is then depicted as following the northeastern margin of the Flagstaff Hill ultramafic mass to where both are cut off on the northwest by the Penryn pluton. The eastern branch is shown somewhat east of the Pine Hill intrusive complex, in a position that would correspond to the southwestern margin of the narrow ultramafic body at Pilot Hill (not shown).

Both of these fault zones were identified in the present study, but the western fault is in a somewhat different position than that shown by Clark (1960). Instead of crossing the amphibolite between the Pine Hill intrusive complex and the ultramafic mass at Flagstaff Hill, this fault zone changes strike from north-northwest to north and continues to follow the western margin of the Pine Hill intrusive complex. The fault along the eastern margin of the Flagstaff Hill mass actually is another fault zone somewhat east of the contact of the ultramafic rocks and the amphibolite. This fault has a northerly strike and is marked by a zone of phyllonite and fissile chlorite schist; it is topographically marked by a remarkably straight alinement of ravines and saddles. The long, narrow lenses of crystalline limestone east of Rattlesnake Bridge and several small lenses of ultramafic rocks are in this zone.

The eastern fault zone indicated by Clark (1960) within the present area follows the long, somewhat sinuous, body of serpentine, but the fault zone is not confined to the serpentine. The adjacent metamorphic rocks are sheared and mylonitized in a zone as much as 500 meters wide in the northern part of the mapped area. The entire body of quartz diorite at Oregon Bar shows the effects of shearing and granulation and may be within the fault zone.

The faults near the northeastern corner of the mapped area deserve special mention. Most of these faults are parallel to the bedding and schistosity and are marked by zones of extremely fissile chlorite schist derived from gabbro and metavolcanic rock by intense shearing, by strongly sheared, talcose ultramafic rock, and by zones of brecciated and mineralized rock. The entire area is characterized by a branching and joining network of faults; only the larger faults are shown on the geologic map (pl. 1).

JOINTS

Almost all the rocks in the area are jointed, but joints were systematically measured only in the Penryn and Rocklin plutons (pl. 1). At most outcrops of these plutons the major joints are more than a meter apart, but in some zones the joints are tens of meters apart and in others the spacing may be only a few centimeters.

The joint pattern in the Penryn and Rocklin plutons seems to be related in part to regional stresses after the time of solidification of these bodies and, in the case of the Penryn pluton, in part to the foliation pattern. Two prominent sets of steeply dipping joints are most evident; one set has an average strike of about N. 30° E., the other, about N. 70° W. These sets seem to cut both plutons without regard to contacts. Among the flat-lying to gently dipping joints, those dipping about 30° to 50° toward the southwest, south, and southeast are most abundant.

The N. 30° E. joint set is occupied at many localities by small quartz veins averaging about 2 to 5 cm in width. Some of the rock adjacent to these veins is gneissic or sheared and is altered to a pale- to medium-green aggregate of sericite, chlorite, and some epidote.

Veins of quartz and dikes of aplite, alaskite, or pegmatite occur in some of the other joint sets, and some of the joints are coated with epidote, chlorite, or quartz. Movement has occurred on a few of these joints, as evidenced by slickensided surfaces of the joint-filling minerals. Displacement generally is directly down the dip of such joints.

FOLDS

The possible existence of isoclinal or nearly isoclinal folds having axes plunging gently north-northwest is suggested by lineations in the amphibolite between the Penryn pluton and the serpentine body that passes through Pilot Hill. However, no crests or troughs of such folds were observed, nor could recognizable lithologic units in the amphibolite be correlated from one limb to another.

The branching outcrop pattern in the northeastern part of the area may reflect either an anticline plunging south-southeast or a syncline plunging north-northwest. Wells, Page, and James (1940) suggested that the ultramafic body at Flagstaff Hill may occupy an asymmetrical northward-plunging anticline. The branching pattern of ultramafic rocks near Pilot Hill may reflect a doubly plunging, nearly isoclinal fold. However, major faulting has complicated the structure at all three of these places, and the outcrop patterns could be ascribed to faults or simply to branching of the ultramafic bodies.

Small folds having amplitudes measured in millimeters or centimeters are abundant in many zones in the metamorphic rocks. These folds consist of contorted bands of epidote and quartz, corrugations of long, needlelike amphibole prisms, and, at some places, of highly crumpled to ptygmatically folded bands in the relatively high grade amphibolite. Plunge of most fold axes is steep. Gently plunging small folds also may be present, but their identification is difficult because of the scarcity of large vertical exposures.

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