Plutonic Rocks of the Klamath Mountains, California and Oregon

GEOLOGICAL SURVEY PROFESSIONAL PAPER 684-B

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By PRESTON E. HOTZ

SHORTER CONTRIBUTIONS TO GENERAL GEOLOGY

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Petrography, chemical composition, and age of plutons of the Klamath Mountains and a comparison with plutons of the east-central and western Sierra Nevada

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1971

UNITED STATES DEPARTMENT OF THE INTERIOR

ROGERS C. B. MORTON, *Secretary*

GEOLOGICAL SURVEY

W. A. Radlinski, *Acting Director*

Library of Congress catalog-card No. 76-171032

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price 35 cents (paper cover)
Stock Number 2401-1129

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PLUTONIC ROCKS OF THE KLAMATH MOUNTAINS, CALIFORNIA AND OREGON

By Preston E. Hotz

ABSTRACT

Pre-Cretaceous sedimentary, volcanic, metamorphic, and ultramafic rocks of the Klamath Mountains province, northwestern California and southwestern Oregon, are intruded by numerous plutons which range from small stocklike bodies to masses of batholithic proportions. Quartz diorite is the most plentiful variety, but the plutons range in composition from diorite and gabbro to quartz monzonite, and some are trondhjemitic. Two small plutons in the eastern part of the province are Permian. All the rest are Middle and Late Jurassic.

Plutons of the Klamath Mountains are similar in composition and age to plutons in the western Sierra Nevada, but contrast sharply in composition with plutons in the east-central Sierra Nevada, which also are generally younger. The fact that the Klamath Mountains and western Sierra Nevada plutons are more sodic than the plutons of the east-central Sierra Nevada possibly reflects fundamental compositional differences in prebatholithic rocks in which magmas were generated by anatexis. Alternatively, a hypothesis correlating increase of K_2O in volcanic rocks with increased depth of magma generation along landward-dipping subduction zones at continental margins may be applicable.

INTRODUCTION

The Klamath Mountains geologic province is an elongate north-trending area of approximately 12,000 square miles in northwestern California and southwestern Oregon. It is bordered on the east by the Cascade province, on the southeast by the Great Valley province of California, and on the west and northwest by the Coast Range provinces of Oregon and California.

Prior to 1960 approximately 12 analyses of plutonic rocks from the Klamath Mountains province had been made; thus the size, shape, distribution, number, and general composition of the plutons were poorly known. In the last decade, however, more attention has been focused on the geology of this region, and several plutons have been mapped (Davis, 1963; Davis and others, 1965; Holdaway, 1962; Hotz, 1967; Lipman, 1963; Romey, 1962; Seyfert, 1965). This report summarizes presently available data on composition and age of the plutons.

GENERAL GEOLOGY

The Klamath Mountains geologic province is divisible into four north-trending arcuate lithologic belts (fig. 1): (1) the eastern Paleozoic belt, (2) the central metamorphic belt, (3) the western Paleozoic and Triassic belt, and (4) the western Jurassic belt. (See Irwin, 1960, p. 16–30; 1966, p. 21–25.)

Rocks of the eastern Paleozoic belt range in age from early Paleozoic to Jurassic and include typically eugeosynclinal clastic sediments and volcanic rocks. They have an aggregate thickness of approximately 40,000–50,000 feet.

Two units make up the central metamorphic belt: the Salmon Hornblende Schist and Abrams Mica Schist. Their metamorphic age is Devonian, as determined by rubidium-strontium techniques (Lanphere and others, 1968).

The western Paleozoic and Triassic belt, the most extensive of the four belts, is an assemblage of fine-grained clastic sedimentary rocks, chert, mafic volcanic rocks, and lenticular marble. The age of these rocks is poorly known, but meager fossil data indicate that they range from late Paleozoic to Late Triassic. The rocks of this belt are, for the most part, regionally metamorphosed and belong to the lower greenschist facies (chlorite subfacies). There are, however, large areas of amphibolites and siliceous metasedimentary rocks of the almandine-amphibolite facies within this belt, and these may be higher grade equivalents of the other rocks. A subcircular "window" of graphitic micaceous schist and actinolite schist, called the schists of Condrey Mountain, underlies the higher grade metamorphic rocks. The schists of Condrey Mountain were metamorphosed in Late Jurassic time, but their parental equivalents are unknown.

The western Jurassic belt is composed of slate and graywacke of the Late Jurassic Galice Formation and

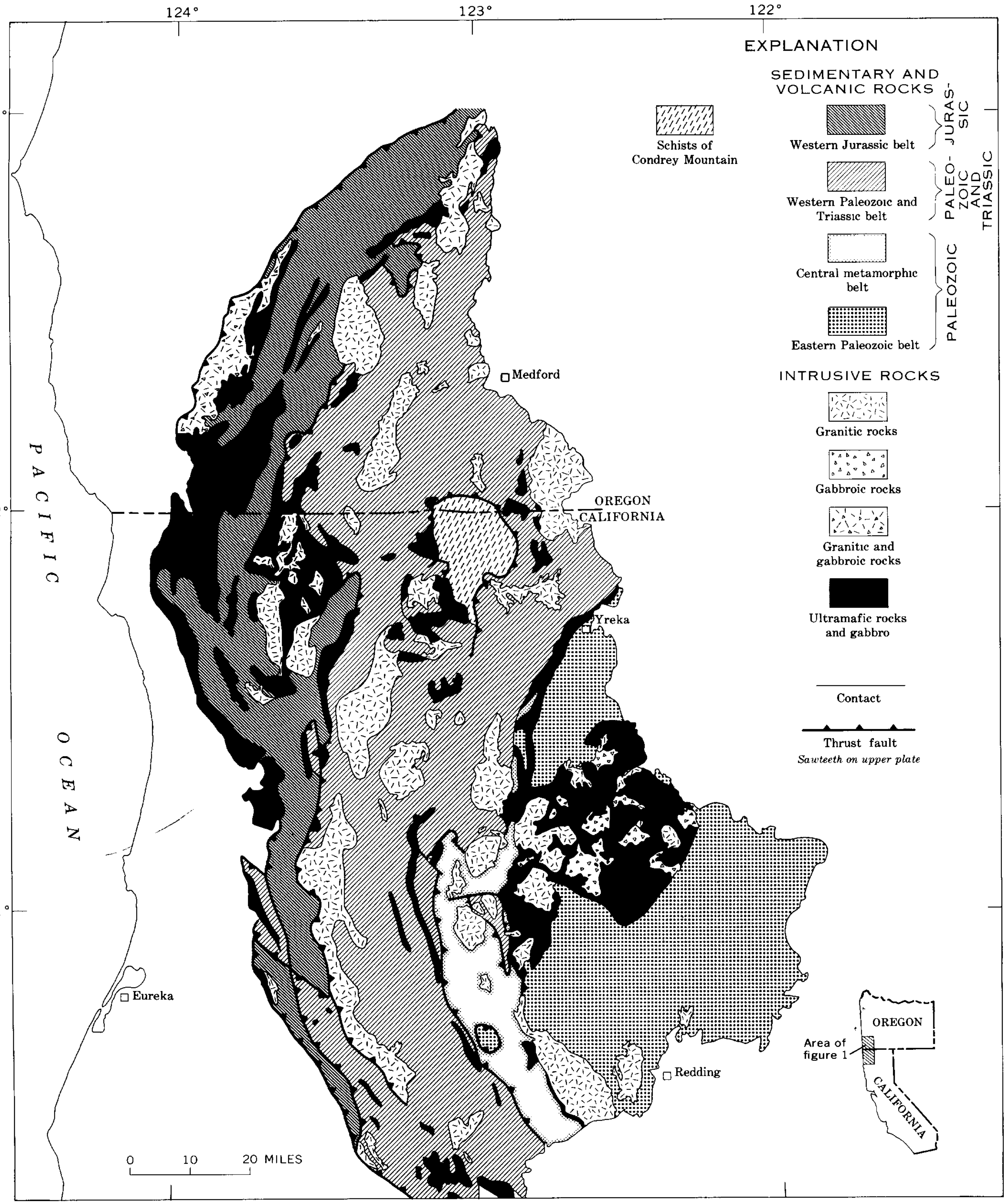

FIGURE 1.—General geology of the Klamath Mountains. Modified from Irwin (1964, fig. 1), Davis, Holdaway, Lipman, and Romey (1965, pl. 1), and Davis (1968, pl. 1).

volcanic rocks that range in composition from basalt to dacite and rhyolite.

The four lithologic belts are bounded by thrust faults along which each belt overrides its western neighbor. In each belt the bedding and (or) metamorphic foliation commonly are inclined to the east. The beds are complexly folded, and the axial planes of the folds commonly dip eastward.

Bodies of ultramafic rock (peridotite and serpentinite) occur in all the lithologic belts. They are commonly elongate and concordant with the structural grain of the province and range in size from a few acres to hundreds of square miles (fig. 1). Several large, continuous, apparently tabular bodies occur along the boundaries between major lithologic belts. Many small, irregularly shaped bodies are possibly remnants of formerly more continuous tabular bodies that were infolded with the rocks they intrude. Mafic rocks that range in composition from diabase to gabbro accompany the ultramafic rocks.

PLUTONIC ROCKS

Granitoid plutonic rocks occur throughout the Klamath Mountains province (figs. 1, 2) and intrude rocks of all four lithologic belts. They are, however, most plentiful in the central metamorphic and western Paleozoic and Triassic belts. The plutons range in size from stocks less than 1 mile in diameter to batholiths with outcrop areas of 100 square miles or more. They tend to be elongate with their long axes parallel to the north-south arcuate trend of the province. Most have been examined only cursorily. Several in the central metamorphic belt have, however, been studied in detail (Davis, 1963; Davis and others, 1965; Lipman, 1963); one of these is cylindrical, and the others have domical internal structures.

In general, too, the intrusions are concordant with the structure of the enclosing rocks. The Vesa Bluffs pluton, northwest of Yreka (Hotz, 1967), and the heterogeneous plutonic mass in Oregon herein called the Chetco River complex (fig. 2), for the major stream which drains much of the area in which it occurs, are tabular, sill-like bodies. The elongate Ironside Mountain pluton in the southwestern part of the province may have a similar geometry.

Classification.—The classification system adopted here (fig. 3) is a common one based on the modal-mineral ratio of quartz-potassium feldspar (including perthite)-plagioclase, recomputed to 100 percent.

Modal composition.—Sixty-seven modes plotted in figure 4 include data from table 1, data from published reports and unpublished theses, and modes determined by the author. These data include measurements made by point counting of thin sections and stained rock slabs.

MAFIC ROCKS

Many of the plutons are partly composed of mafic rocks whose modal compositions plot near the plagioclase corner of the quartz-plagioclase-potassium feldspar triangular diagram (fig. 4). Some of the mafic rocks form relatively small bodies wholly or partly enclosed by more felsic rocks, which constitute the major part of a pluton. Some larger bodies are mafic parts of composite plutons that are predominantly more silicic. The intimate association strongly suggests a consanguineous relationship between the mafic and more silicic members of a pluton. Some diorites and gabbros associated with the ultramafic bodies have isotopic ages that are distinctly older than any of the granitic plutons which have been dated (Lanphere and others, 1968, p. 1043–47; R. G. Coleman, written commun. 1970). These older rocks are not described here.

The mafic members are dark medium-grained hypidiomorphic-granular rocks which are classified as gabbros or diorites depending on the anorthite content of their plagioclase. Rocks classified as gabbro commonly contain 40–60 percent mafic minerals, and the plagioclase is more calcic than An_{50}. Most diorites contain 35–60 percent mafic minerals, somewhat less than gabbro, and the plagioclase is less calcic than An_{50} (35–45 percent anorthite in most specimens).

Pyroxene is the dominant mafic mineral in some of the gabbros, although some hornblende is commonly present. Both orthopyroxene and clinopyroxene are generally present. The common varieties of gabbro in many composite plutons, however, have hornblende as the principal mafic constituent, which may or may not be accompanied by pyroxene. Plagioclase is well twinned and strongly zoned. Its average composition may range from approximately An_{55} to An_{80}, but most commonly is between An_{55} and An_{65}; the range in zoned crystals may be very wide, and An_{35} to An_{80} is not unusual. Quartz is a minor constituent (less than 10 percent) of most hornblende gabbros.

Hornblende is the dominant mafic mineral of the diorites and is commonly accompanied by small amounts of biotite. Pyroxene, generally relict grains enclosed by hornblende, occurs in small, variable amounts in many specimens. The plagioclase averages about 35 to 45 percent anorthite, although zoned crystals may range from An_{25} to An_{50}. Small amounts of quartz (less than 10 percent) are present in many of the diorites. Some of these quartz-bearing diorites plot on the lower part of the quartz-plagioclase join above the 10-percent-quartz boundary on the modal triangular diagram.

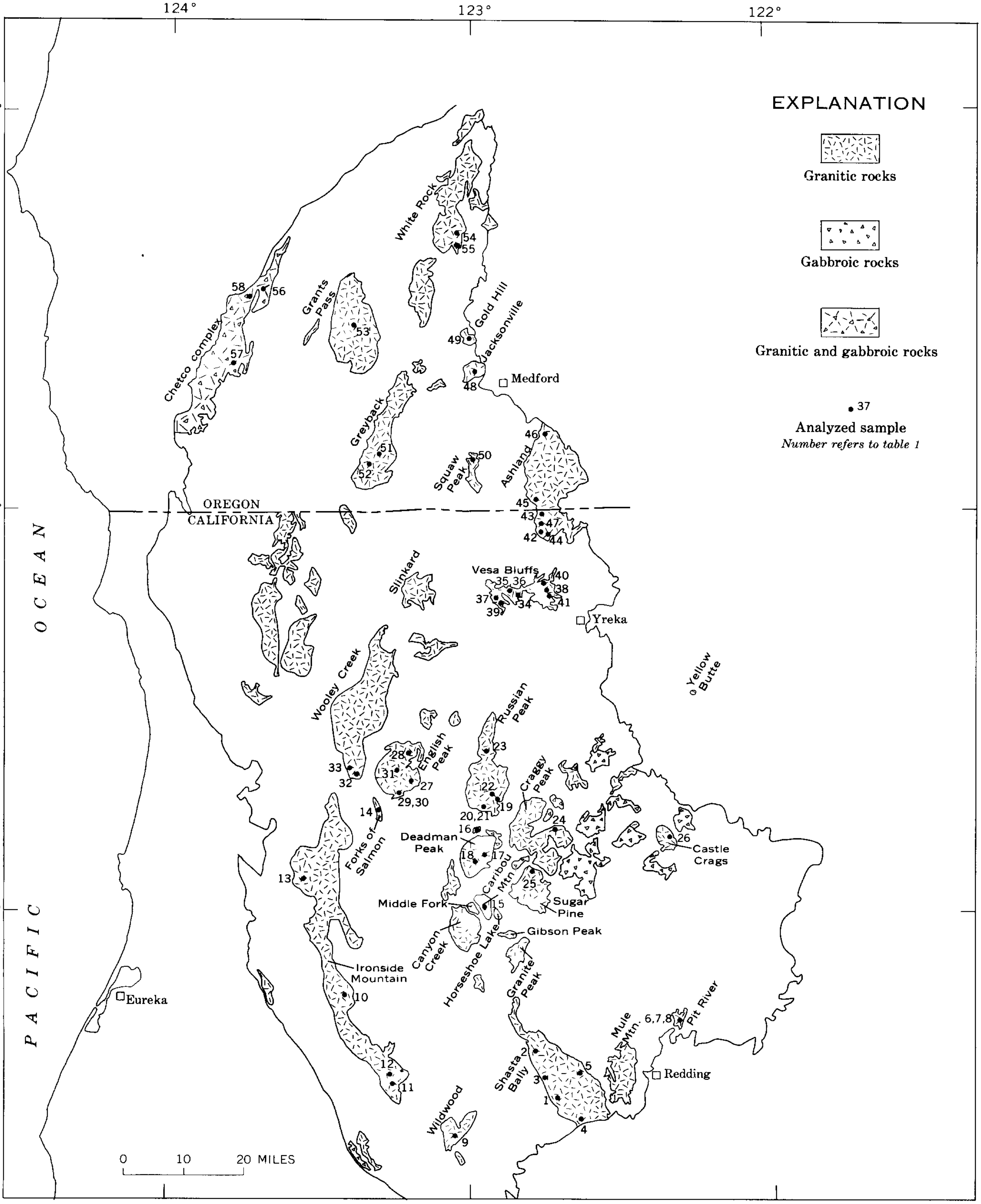

FIGURE 2.—Plutons of the Klamath Mountains.

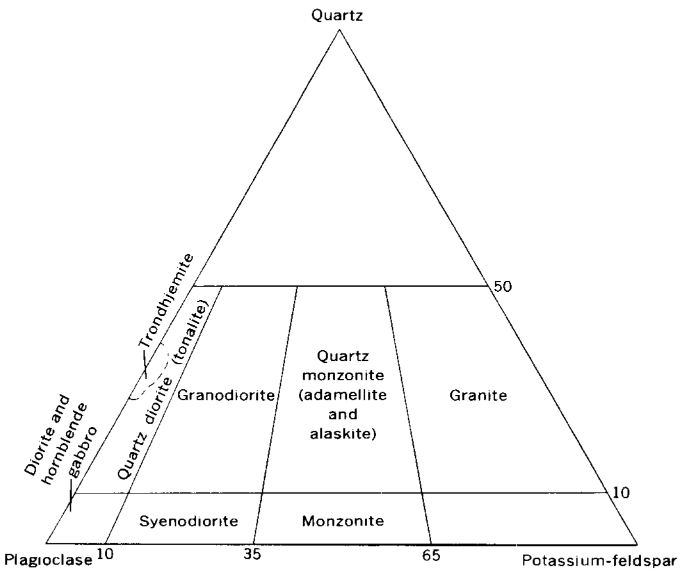

FIGURE 3.—Classification system used for plutonic rocks of the Klamath Mountains.

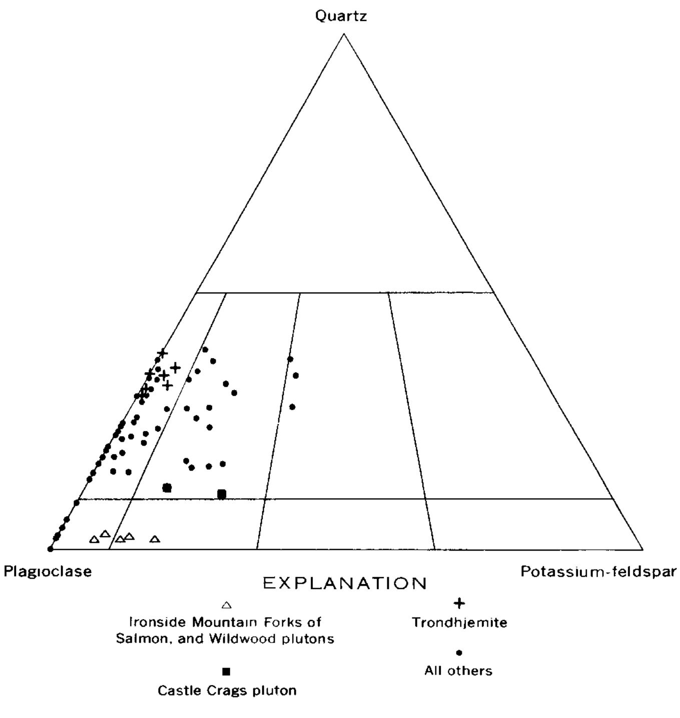

FIGURE 4.—Modal quartz-plagioclase-potassium feldspar ratio for plutons of the Klamath Mountains.

SYENODIORITE

Four specimens collected for age determinations (Lanphere and others, 1968)—three from the Ironside Mountain pluton and one from the Forks of Salmon pluton—constitute an unusual variety of mafic rock, syenodiorite, according to Johannsen's (1939) system of classification. On the quartz-plagioclase-potassium feldspar diagram (fig. 4), the specimens plot near the plagioclase corner in the syenodiorite and gabbro fields.

The rocks are dark (color index 33–48), fine to medium grained, and hypidiomorphic granular. They contain up to 2 percent interstitial quartz and 46–57 percent plagioclase, which ranges from calcic oligoclase (An_{25}) to calcic labradorite (An_{65}). They also contain 4–11 percent of anhedral intergranular potassium feldspar. The predominant mafic mineral is anhedral to subhedral pyroxene, most of which is hypersthene and the rest augite. Biotite is a minor constituent. In the specimen from the Forks of Salmon pluton, hornblende, which has replaced pyroxene, is the chief mafic mineral. A similar but lighter rock (color index 21) from the Russian Peak pluton was described by Romey (1962) as a monzonitic pyroxene-biotite diorite.

QUARTZ DIORITE

Quartz diorite is the commonest plutonic rock of the Klamath Mountains. Its color index ranges from less than 10 to about 40. Rocks whose dark minerals amount to 15–35 percent are most abundant, but light-colored varieties whose index is less than 10 are plentiful in some plutons. The rocks are hypidiomorphic granular and fine to medium grained.

The quartz content ranges from 10 to approximately 35 percent. Subhedral to euhedral plagioclase amounting to 50–65 percent in most of the quartz diorite is generally strongly zoned and ranges in composition from approximately An_{20} to An_{60} (calcic oligoclase to medium labradorite; average composition probably is in the range of andesine).

Potassium feldspar is a minor constituent in many of the plutonic rocks called quartz diorite, but is absent from many others. It occurs interstitially in amounts that range from a trace to 5 percent and is usually untwinned, although some shows microcline-type grid twinning under the microscope.

Hornblende is the predominant mafic mineral and usually occurs as euhedral crystals, although in some specimens it forms ragged grains. In some specimens it contains cores of partly replaced relict augite. Biotite accompanies hornblende, but in somewhat smaller amounts. It occurs as discrete plates and as irregular masses intergrown with and forming rims around hornblende.

TRONDHJEMITE

The younger, innermost parts of some composite and zoned plutons are trondhjemitic in composition (Davis, 1963; Davis and others, 1965; Lipman, 1963). From the limited data presently available, it appears that trondhjemite plutons are among the youngest in the

TABLE 1.—*Chemical and spectrographic analyses, norms,*

[Analyses from sources given in localities list at end of table, except as follows: Chemical analyses: specimen 45, standard analysis by F. S. Grimaldi; 46, 48–58, rapid analyses 39 analyzed by W. B. Crandell; 46, 48–58 by Chris Heropoulos; 37, 38, 41–44. 47 by R. E. Mays; 34, 40 by C. H. Pickett; results reported to the nearest number in the series 1, the quantitative value about 30 percent of the time. Modes: for characterizing accessories, B=biotite, H=hornblende, P=pyroxene, M=muscovite]

Pluton	Shasta Bally					Pit River			Wildwood	Ironside Mountain			
Specimen No.	1	2	3	4	5	6	7	8	9	10	11	12	13
Field No.	L-5	A-5-64	D-24		BB-38	65 Cle 3			66 Cle 26	65 Cle 29	66 Cle 27	66 Cle 28	65 Cle 33
Chemical analyses													
SiO	64.5	67.4	68.0	68.10	70.4	71.3	63.09	63.26	50.1	50.1	51.6	51.6	53.1
Al_2O_3	16.3	15.0	16.0	15.18	15.9	15.0	16.04	15.80	18.0	16.3	17.5	15.2	14.9
Fe_2O_3	1.6	1.3	1.5	1.34	.9	.61	1.33	1.45	3.4	2.1	2.2	2.7	1.4
Total Fe as FeO	(3.9)	(3.5)	(2.9)	(2.9)	(2.2)	(2.5)	(5.6)	(5.4)	(10.7)	(11.0)	(9.6)	(10.4)	(10.9)
FeO	2.5	2.3	1.5	1.70	1.4	1.9	4.40	4.07	7.6	9.1	7.6	8.0	9.6
MgO	2.9	2.3	2.0	2.06	1.3	.8	2.48	2.47	4.8	4.8	5.1	5.8	5.3
CaO	4.1	4.0	4.1	4.66	3.2	3.3	5.00	4.31	9.6	8.7	9.7	10.3	8.4
Na_2O	4.0	3.2	3.8	3.71	4.0	3.7	3.85	4.53	2.8	2.7	2.7	2.4	2.5
K_2O	2.0	2.4	2.2	1.48	2.5	1.8	.91	1.06	.75	2.1	1.2	1.7	2.4
H_2O^-	1.6 (H₂O− and H₂O+)	.74	.56 (H₂O− and H₂O+)	.55 (H₂O− and H₂O+)	.56 (H₂O− and H₂O+)	.15	1.94	2.01	.13	.11	.09	.05	.11
H_2O^+		.13				1.0	.12	.14	1.1	1.5	1.0	.95	.71
TiO_2	.48	.41	.33	.35	.28	.25	.53	.48	.79	1.0	.17	.17	.99
P_2O_5	.10	.09	.09	.18	.07	.03			.33	.5	.32	.31	.37
MnO	.06	.05	.04	.20	.04	.09			.07	.12	.26	.10	.07
BaO				.06									
CO_2	<.05	.05	<.05		<.05				<.05	<.05	<.05	<.05	<.05
Total	100.00	99.00	100.00	99.57	101.00	100.00	99.69	99.58	99.00	99.00	99.00	99.00	100.00
Semiquantitative spectrographic													
B													
Ba													
Be													
Co													
Cr													
Cu													
Ga													
La													
Nb													
Ni													
Pb													
Sc													
Sr													
V													
Y													
Yb													
Zr													
Norms (weight													
Q	19.6	27.0	25.9	27.54	31.2	33.5	19.7	17.8	2.0		1.2	0.7	1.4
C	.4	.2	.3		1.0	1.0							
or	11.0	14.3	12.8	8.90	15.0	10.7	5.3	6.2	4.4	12.4	7.1	10.0	14.2
ab	34.1	27.3	32.0	31.44	29.9	31.4	32.6	38.3	23.7	22.8	22.8	20.3	21.2
an	19.5	19.1	18.9	20.29	15.0	16.2	23.8	19.7	34.3	26.2	32.1	25.7	22.3
wo							.4	.7	4.6	5.7	5.8	9.8	7.1
en		5.8				2.0	7.2	6.2	11.9	9.7	12.7	14.4	13.2
fs		2.6				2.7	6.1	5.5	10.0	11.0	12.3	12.4	15.0
di				1.84									
hy	9.8		6.1	6.18	4.4								
fo										1.5			
fa										1.9			
mt	2.3	1.9	2.1	1.86	1.4	.9	1.0	2.1	4.9	3.0	3.2	3.9	2.0
il	.9	.8	.6	.91	.6	.5	1.9	.9	1.5	1.9	.3	.3	1.9
ap	.3	.2	.3	.34	.3	.1				1.2	.8	.7	.9
cc		.1											
Total	97.9	99.3	99.0	99.30	98.8	99.00	97.0	97.4	97.3	97.3	98.3	98.2	99.2
Modes (volume													
Quartz		32				35			2	2		<1	1
Potassium feldspar		8				6				5		6	11
Plagioclase		47				49			65	57		46	51
Mafic minerals		13				10			33	36		48	36
Characterizing accessories		B,H				B,H			P,B	P,B		P,B	P,B

and modes of plutonic rocks of the Klamath Mountains

by P. L. D. Elmore, S. D. Botts, Gillison Chloe, Lowell Artis, James Kelsey, Hezekiah Smith, and J. L. Glenn. Semiquantitative spectrographic analyses: specimens 35, 36, 0.7, 0.5, 0.3, 0.2, 0.15, and 0.1, etc., which represent approximate midpoints of group data on a geometric scale; the assigned interval for semiquantitative results will include

Forks of Salmon	Caribou Mountain	Deadman Peak			Russian Peak					Craggy Peak	Sugar Pine	Castle Crags	English Peak		
14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
66 Cle 17	14-33	3317	3617	272	173	157	159	175	613	65 Cle 6	65 Cle 8	66 Cle 1	2-818	2-19	65 Cle 19
(weight percent)															
53.1	68.58	58.87	67.68	66.67	50.64	53.99	56.14	64.37	69.87	70.5	60.8	66.5	58.0	59.0	61.1
16.5	17.10	15.82	15.89	15.52	16.67	16.85	18.01	15.77	16.26	16.4	16.6	17.7	16.0	17.0	16.5
1.8	.76	1.25	1.54	1.74	3.49	2.17	2.75	2.05	1.09	.79	2.4	1.0	1.54	1.1	.84
(8.3)	(2.1)	(5.9)	(3.3)	(3.4)	(9.2)	(7.8)	(7.1)	(4.4)	(2.4)	(1.8)	(5.6)	(2.2)	(7.72)	(5.29)	(5.4)
6.7	1.44	4.76	1.94	1.83	6.07	5.82	4.61	2.56	1.46	1.1	3.4	1.3	6.33	4.2	4.6
5.3	1.18	5.34	2.04	2.17	6.33	3.90	2.50	1.62	.18	.87	3.0	.91	4.8	3.5	3.6
8.6	4.40	5.82	3.71	3.79	10.78	7.71	6.61	4.61	2.85	3.4	6.0	3.3	7.8	6.8	5.8
3.7	4.69	3.56	4.30	4.17	3.19	4.03	4.24	4.13	4.77	4.7	3.7	5.2	2.95	3.3	3.3
1.1	.96	1.44	1.62	1.99	.18	1.64	2.16	2.56	2.10	.95	1.4	2.7	1.94	2.27	1.5
.18		.35	.28	.25	.14	.44	.36	.23	.34	.44	.64	.11			1.0
1.9	.58	2.12	.68	.67	.90	1.68	1.03	1.09	.75	.06	.16	.50			.16
.76	.29	.85	.45	.50	.65	.90	.80	.45	.30	.28	.74	.25	.70	.62	.69
.11	.11	.32	.17	.28	.34	.39	.35	.22	.13	.02	.15	.14			.14
.07	.23	.10	.05	.06	.15	.12	.11	.07	.04	.06	.15	.10	.14	.10	.10
<.05										<.05	<.05	<.05			
100.00	100.32	100.60	100.35	99.64	99.53	99.64	99.67	99.73	100.14	100.00	99.00	100.00	100.00	98.00	99.00
analyses (weight percent)															
percent)															
0.6	25.5	11.0	25.2	23.7	0.9	2.1	5.5	18.8	27.5	30.7	16.6	17.4	8.2	10.1	16.2
	.61		.7	.3					1.3	1.5		.6			
6.5	5.56	8.5	9.6	11.8	1.1	9.7	12.8	15.1	12.4	5.6	8.4	16.0	11.4	13.7	8.9
31.3	39.82	30.1	36.4	35.3	27	34.5	35.9	34.9	40.4	40.0	31.6	44.2	24.9	29.6	28.29
25.2	20.85	22.9	17.3	17.0	30.6	22.8	23.7	16.9	13.3	16.8	24.8	15.5	24.6	24.8	26
7.0		1.6			8.6	5.4	2.8	1.9			1.8		5.8	4.0	.9
13.2		13.3	5.1	5.4	15.8	9.7	6.2	4.0	.4	2.2	7.5	2.3	11.9	8.9	9.0
9.7		6.5	1.6	1.2	7.4	7.6	5.1	2.4	1.4	1.0	3.3	1.3	9.4	6.1	6.8
	5.14														
2.6	1.16	1.8	2.2	2.5	5.1	3.1	4.0	3.0	1.6	1.2	3.5	1.5	2.2	1.6	1.2
1.4	.61	1.6	.9	1.0	1.2	1.7	1.5	.9	.6	.5	1.4	.5	1.3	1.2	1.3
.3	.34	.8	.4	.7	.8	.9	.8	.5	.3	.05	.4	.3			.3
97.8	99.59	98.1	99.4	98.9	98.5	97.5	98.3	98.4	99.2	99.55	99.3	99.6	99.7	100.00	98.8
percent)															
<1	28.6	11.3	23.4	28.5		2.6	1.6	21.6	23.7	27	16	11	9.6	20.5	16
4	1.1		5.9	16.5			10.2	10.0	8.8	1	4	13	3.6	9.5	Trace
50	64.2	55.0	56.1	42.7	60.9	53.8	68.5	51.8	56.8	65	56	67	50.4	43.2	55
46	6.1	33	15	12	39	43	21	16	10	7	23	9	36.4	26.9	29
P,H	B,H	B,H	B,H	B,H	P,H	P,B,H	P,B	B,H	B	B	B,H	B,H	P,B,H	B,H	

TABLE 1.—*Chemical and spectrographic analyses, norms,*

[Analyses from sources given in localities list at end of table, except as follows: Chemical analyses: specimen 45, standard analysis by F. S. Grimaldi; 46, 48–58, rapid analyses 35, 36, 39 analyzed by W. B. Crandell; 46, 48–58 by Chris Heropoulos; 37, 38, 41–44, 47 by R. E. Mays; 34, 40 by C. H. Pickett; results reported to the nearest number in will include the quantitative value about 30 percent of the time. Modes: for characterizing accessories, B=biotite, H=hornblende, P=pyroxene, M=muscovite]

Pluton	English Peak		Wooley Creek		Vesa Bluffs							
Specimen No.	30	31	32	33	34	35	36	37	38	39	40	41
Field No.	66 Cle 18	2-731	66 Cle 20	66 Cle 21	CM 20–62	CM 99–64	CM 100–64	CM 118–63	CM 109–63	CM 89–64	CM 29–60	CM 108–63
Chemical analyses												
SiO_2	68.3	74.0	56.4	64.6	46.5	50.9	53.9	60.0	61.1	63.5	64.2	74.6
Al_2O_3	15.3	14.0	15.6	15.4	18.0	18.7	16.2	17.2	17.2	16.4	16.9	14.6
Fe_2O_3	1.0	.37	.89	1.2	2.9	1.4	2.4	1.7	2.6	.79	2.4	.53
Total Fe as FeO	(3.3)	(1.92)	(8.0)	(4.6)	(11.1)	(7.6)	(7.9)	(6.0)	(5.7)	(4.8)	(4.9)	(0.6)
FeO	2.4	1.59	7.1	3.5	8.5	6.3	5.7	4.5	3.4	4.1	2.7	.16
MgO	1.4	.78	4.8	2.4	6.2	4.5	5.4	2.9	2.3	2.0	1.9	.26
CaO	4.1	2.4	8.0	4.8	10.9	10.5	10.0	6.8	7.5	4.6	6.2	.10
Na_2O	3.0	3.65	2.4	3.1	2.7	3.5	2.7	2.8	3.2	3.9	2.8	4.7
K_2O	2.7	3.70	1.8	2.5	.50	1.0	1.1	1.4	1.1	2.5	1.6	4.6
H_2O^-	.07		.11	.12	.07	.19	.09	.19	.10	.12	.11	.12
H_2O^+	.73		1.1	1.1	2.2	1.6	1.3	1.7	.95	1.2	1.0	.65
TiO_2	.27	.22	.77	.43	.94	.73	.65	.39	.29	.49	.33	.04
P_2O_5	.04		.15	.08	.36	.18	.15	.23	.35	.14	.17	.01
MnO	.07	.05	.11	.13	.21	.14	.16	.15	.14	.15	.14	.03
BaO												
CO_2	<.05		.11	<0.05	<.05	.19	.11	<.05	<.05	.05	<.05	<.05
Total	99.00	101.00	99.00	99.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Semiquantitative spectrographic												
B					<0.003						<0.003	
Ba					.02	0.03	0.05	0.07	0.05	0.1	.1	0.01
Be												.0003
Co					.003	.003	.002	.0015	.0015	.001	.0015	
Cr					.002	.007	.003	.0007	.0017	.002	.002	.0002
Cu					.07	.0015	.01	.007	.007	.001	.003	.0005
Ga					.0015	.0015	.001	.0015	.0015	.001	.0015	.0015
La												
Nb												
Ni					.003	.005	.005	.0005	.0005	<.003		
Pb					.002						.003	
Sc					.003	.003	.003	.0015	.0015	.001	.0015	
Sr					.1	.07	.05	.15	.1	.05	.15	.007
V					.03	.02	.02	.015	.015	.01	.015	
Y					.003	.0007	.001	.0015	.0015	.0007	.002	
Yb					.0003		.0001	.0002	.0002		.0002	.0001
Zr					.003	.003	.001	.005	.007	.007	.01	.01
Norms (weight												
Q	28.5	31.2	9.4	21.8			5.8	17.6	19.2	16.4	25.1	29.1
C	.1											1.7
or	16.1	21.7	10.7	14.9	3.0	5.9	6.5	8.3	6.5	14.8	9.4	27.2
ab	25.6	30.6	20.5	26.4	22.8	29.6	22.8	23.7	27.1	33.0	23.7	39.8
an	20.2	10.8	26.7	20.9	35.5	32.4	28.8	30.3	29.3	19.9	28.8	.4
wo		.4	4.8	1.1	6.8	7.2	8.0	.8	2.3	.7	.3	
en	3.5	1.9	12.0	6.0	5.6	7.1	13.5	7.2	5.7	5.0	4.7	.6
fs	3.3	2.3	11.3	5.0	4.4	6.0	7.7	6.5	3.9	6.3	2.7	
di												
hy												
fo					6.9	2.9						
fa					5.9	2.7						
mt	1.5	.5	1.3	1.8	4.2	2.0	3.5	2.5	3.8	1.1	3.5	.5
il	.5	.4	1.5	.8	1.8	1.4	1.2	.7	.6	.9	.6	.1
ap	.1		.4	.2	.8	.4	.4	.5	.8	.3	.4	<.1
cc			.2			.4	.2			.1		
Total	99.4	99.8	98.8	98.9	97.7	98.0	98.4	98.1	99.2	98.4	99.2	99.4
Modes (volume												
Quartz	31	33.8	10	25	1		7	16	17	22	24	33
Potassium feldspar	7	20.2	2	13				1		5	1	24
Plagioclase	51	37.5	53	43	44	59	43	56	57	52	51	40
Mafic minerals	11	8.5	35	19	50	41	50	25	24	20	24	3
Characterizing accessories		B	P,B,H	B,H	H	H	H	B,H	B,H	B,H	B,H	M

and modes of plutonic rocks of the Klamath Mountains—Continued

by P. L. D. Elmore, S. D. Botts, Gillison Chloe, Lowell Artis, James Kelsey, Hezekiah Smith, and J. L. Glenn. Semiquantitative spectrographic analyses: specimens the series 1, 0.7, 0.5, 0.3, 0.2, 0.15, and 0.1, etc., which represent approximate midpoints of group data on a geometric scale; the assigned interval for semiquantitative results

Ashland						Jacksonville	Gold Hill	Squaw Peak	Greyback		Grants Pass	White Rock		Chetco River complex		
42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58
CM 27-63	CM 59-63	CM 26-63	PEH 116-38	ASH 7-67	CM 77-63	MED-1-67	MED-3-67	TL 2-67	OC-1-67	OC-2-67	GP 1-67	WI-8-67	WI-9-67	GAL-11-67	PP-1-67	GAL-12-67
(weight percent)																
49.5	52.1	57.9	57.85	62.3	63.3	65.0	68.1	58.2	48.7	66.0	69.4	69.2	70.8	49.6	52.9	62.1
13.8	10.7	14.9	17.57	16.3	15.8	16.7	16.1	18.0	16.4	16.4	15.9	17.6	17.5	17.7	17.7	17.5
1.0	1.2	1.2	1.98	1.3	1.3	1.8	1.2	3.2	2.3	1.8	.86	1.0	.33	1.1	4.3	2.5
(10.7)	(7.5)	(7.7)	(7.0)	(4.5)	(4.2)	(3.6)	(2.6)	(6.7)	(11.2)	(4.4)	(2.2)	(2.1)	(1.2)	(8.9)	(10.4)	(5.2)
9.8	6.4	6.6	5.22	3.2	3.0	1.9	1.4	3.7	8.9	2.7	1.4	1.1	.88	7.7	6.3	2.8
8.6	11.7	6.1	3.42	3.3	3.4	2.2	1.4	2.9	9.0	1.0	1.3	.69	.41	7.9	4.5	2.0
11.4	12.6	7.9	7.06	5.4	6.1	3.8	2.8	7.0	11.3	4.8	2.6	3.6	3.4	11.6	8.7	5.8
1.6	1.7	2.5	3.27	3.5	3.9	4.9	5.1	3.0	1.3	3.8	4.6	4.8	4.7	1.4	2.5	3.3
.44	.82	1.2	1.29	2.9	1.4	1.8	2.5	1.7	.14	1.4	2.4	.84	.95	.06	.20	1.4
.12	.34	.16	.07	.05	.20	.11	.09	.17	.07	.27	.10	.09	.07	.22	.21	.12
1.2	1.1	.52	.33	.54	1.0	.51	.55	1.2	.45	.93	.82	.67	.52	1.9	.78	1.1
1.4	.78	.84	1.04	.66	.48	.56	.40	.49	.76	.46	.28	.24	.13	.40	.75	.61
.60	.16	.34	.36	.35	.26	.17	.12	.16	.08	.12	.11	.09	.04	.13	.15	.24
.21	.15	.13	.12	.13	.10	.11	.07	.17	.22	.10	.08	.06	.05	.20	.21	.17
<.05	<.05	<.05	.14	<.05	.17	<.05	<.05	<.05	.11	.05	.05	<.05	<.05	<.05	<.05	<.05
100.00	100.00	100.00	99.72	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.00	100.00
analyses (weight percent)																
----	0.0007	0.0015	----	0.002	0.0015	----	0.001	0.0015	----	0.001	0.0015	0.001	0.0015	----	----	----
0.02	.03	.05	----	.1	.07	0.05	.05	.05	0.01	.07	.1	.03	.03	0.003	0.01	0.07
----	----	----	----	.0003	----	.00015	.0002	----	----	----	.00015	----	.0001	----	----	----
.003	.003	.002	----	.002	.001	.001	.0007	.002	.007	.0007	.0007	.0005	.0002	.005	.005	.0015
.07	.02	.03	----	.007	.003	.005	.003	.001	.015	.0005	.003	.001	.0005	.005	.0007	.001
.007	.015	.01	----	.005	.005	.0007	.0005	.01	.03	.0015	.005	.0015	.001	.01	.02	.0015
.0015	.001	.0015	----	.0015	.0015	.002	.0015	.0015	.0015	.002	.002	.002	.0015	.0015	.002	.002
----	----	----	----	.005	----	----	----	----	----	.003	----	----	----	----	----	.005
----	----	----	----	.001	----	.0007	.0007	----	.0007	.001	.0007	----	----	.001	----	.0015
.01	.015	.003	----	.005	.001	.002	.002	.0007	.007	----	.0015	.0005	.0001	.005	.0015	.0005
----	.002	----	----	.002	.002	.001	.001	.001	----	.001	.002	.0007	.001	----	----	.001
.003	.005	.002	----	.002	.0015	.001	.0007	.002	.007	.0015	.001	.0005	----	.007	.002	.002
.1	.05	.07	----	.1	.15	.1	.07	.07	.07	.05	.1	.1	.1	.05	.07	.07
.03	.03	.02	----	.01	.01	.007	.005	.02	.07	.005	.005	.005	.0015	.03	.01	.01
.002	.002	.002	----	.002	.002	.002	.001	.002	.001	.002	.0007	.0007	----	.0015	.002	.002
.0002	.0002	.0003	----	.0002	.0002	.0002	.0001	.0002	.0015	.0002	.0001	.0007	----	.0002	.00015	.00015
----	.01	.01	----	.015	.01	.007	.01	.003	.0015	.02	.007	.01	.007	.0007	.015	.015
percent)																
1.1	----	11.6	12.63	14.5	17.9	18.2	20.7	14.4	0.8	26.0	25.7	29.2	31.6	2.3	10.7	21.8
----	----	----	----	----	----	.2	.2	----	----	.3	1.4	2.5	2.7	----	----	.6
2.6	4.8	7.1	7.62	17.2	8.3	10.7	14.8	10.1	.8	8.3	14.2	5.0	5.6	.4	1.2	8.3
13.5	14.4	21.2	27.67	29.6	33.0	41.7	43.3	25.5	11.0	32.3	39.0	40.7	39.9	11.9	21.4	28.1
29.2	19.1	25.9	29.45	20.2	21.5	17.8	13.1	30.7	38.6	22.8	11.9	17.3	16.6	42.0	36.8	27.3
9.8	17.7	4.6	.98	1.8	2.5	----	----	1.3	6.8	----	----	----	----	6.2	2.4	----
21.4	28.6	15.2	8.52	8.2	8.5	5.5	3.5	7.2	22.5	2.5	3.2	1.7	1.0	19.7	11.3	5.0
15.2	9.6	10.0	6.46	4.0	3.8	1.3	1.0	3.7	13.6	2.9	1.6	.9	1.2	13.0	7.2	2.4
----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----
----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----
----	.4	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----
----	.1	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----
1.4	1.7	1.7	2.87	1.9	1.9	2.6	1.7	4.6	3.3	2.6	1.2	1.4	.5	1.6	6.3	3.6
2.7	1.5	1.6	1.98	1.3	.9	1.1	.8	.9	1.4	.9	.5	.5	.3	.8	1.4	1.2
1.4	.4	.8	.85	.8	.6	.4	.3	.4	.2	.3	.3	.2	.1	.3	.4	.6
----	----	----	.32	----	.4	----	----	----	.2	.1	.1	----	----	----	----	----
98.3	98.3	99.7	99.35	99.5	99.3	99.5	99.4	98.8	99.2	99.0	99.1	99.4	99.5	98.2	99.1	98.9
percent)																
Trace	2	12	14	13	18	20	22	18	----	31	26	31	35	8	12	26
----	----	----	----	16	Trace	4	14	5	----	1	25	----	----	----	----	2
40	19	49	56	48	54	61	56	53	49	57	42	61	60	39	54	62
60	68	39	30	23	27	15	8	24	51	12	7	8	5	53	35	10
P,H	P,H	P,B,H	----	P,H	P,H	B,H	B,H	----	P,H	B,H	B,H	B,M	B,M	H	P,H	B,H

(For locality descriptions, see following page.)

LOCALITIES FOR TABLE 1

1. Quartz diorite; 40°30'30'' N., 122°40'30'' W. (Albers, 1964, table 2).
2. Granodiorite; 40°40' N., 122°47' W. (Lanphere and others, 1968, table 8, sample 35).
3. Quartz diorite; 40°34' N., 122°44' W. (Albers, 1964, table 2).
4. No name given; approximately 40°29' N., 122°37' W. (Albers, 1964, table 2, sample A).
5. Quartz diorite; 40°36' N., 122°39' W. (Albers, 1964, table 2).
6. Granodiorite; 40°45' N., 122°19' W. (Lanphere and others, 1968, table 5, sample 22).
7. Quartz diorite; 40°44' N., 122°19' W. (Hinds, 1935, p. 345).
8. No name given; 40°44' N., 122°19' W. (Hinds, 1935, p. 345).
9. Pyroxene diorite; 40°27' N., 123°4' W. (Lanphere and others, 1968, table 6).
10. Syenodiorite; 40°47' N., 123°25' W. (Lanphere and others, 1968, table 6, sample 23).
11. Syenodiorite; 40°35' N., 123°15' W. (Lanphere and others, 1968, table 6).
12. Syenodiorite; 40°36' N., 123°16' W. (Lanphere and others, 1968, table 6).
13. Syenodiorite; 41°05'30'' N., 123°34' W. (Lanphere and others, 1968, table 6, sample 24).
14. Syenodiorite; 41°16' N., 123°18'30'' W. (Lanphere and others, 1968, table 6, sample 25).
15. Calcic trondhjemite; approximately 41°1' N., 122°58' W. (Davis, 1963, p. 344).
16. Quartz diorite; approximately 41°12' N., 122°58' W. (Holdaway, 1962).
17. Quartz diorite; approximately 41°10' N., 122°58' W. (Holdaway, 1962).
18. Granodiorite; approximately 41°8' N., 122°58' W. (Holdaway, 1962).
19. Pyroxene diorite; approximately 41°17' N., 122°54'30'' W. (Romey, 1962).
20. Diorite; approximately 41°16' N., 122°57'30'' W. (Romey, 1962).
21. Quartz diorite; approximately 41°16' N., 122°57'30'' W. (Romey, 1962).
22. Granodiorite; approximately 41°17'30'' N., 122°54'30'' W. (Romey, 1962).
23. Granodiorite; approximately 41°24' N., 122°57' W. (Romey, 1962).
24. Trondhjemite; 41°13'30'' N., 122°43' W. (Lanphere and others, 1968, table 8, sample 33).
25. Quartz diorite; 40°41' N., 122°45' W. (Lanphere and others, 1968, table 8, sample 34).
26. Granodiorite; 41°11'30'' N., 122°19' W. (Lanphere and others, 1968, table 5, sample 21a).
27. Quartz diorite; 41°20' N., 123°12' W. (Seyfert, 1965, p. 80).
28. Granodiorite; 41°24' N., 123°13' W. (Seyfert, 1965, p. 80).
29. Quartz diorite; 40°41' N., 122°45' W. (Lanphere and others, 1968, table 8, sample 36).
30. Granodiorite; 40°41' N., 122°45' W. (Lanphere and others, 1968, table 7).
31. Granodiorite; 41°22' N., 123°15' W. (Seyfert, 1965, p. 80).
32. Diorite; 41°20'30'' N., 123°22'30'' W. (Lanphere and others, 1968, table 7).
33. Granodiorite; 41°21' N., 123°24' W. (Lanphere and others, 1968, table 7).
34. Gabbro; 41°47'30'' N., 122°50' W. (Lanphere and others, 1968, table 7).
35. Diorite; 41°48' N., 122°51'30'' W. (Lanphere and others, 1968, table 7).
36. Quartz diorite; 41°47'30'' N., 122°51'30'' W. (Lanphere and others, 1968, table 7).
37. Quartz diorite; 41°48' N., 122°56' W. (Lanphere and others, 1968, table 7).
38. Quartz diorite; 41°48'30'' N., 122°45'30'' W. (Lanphere and others, 1968, table 7).
39. Quartz diorite; 41°46'30'' N., 122°54'30'' W. (Lanphere and others, 1968, table 7).
40. Quartz diorite; 41°49' N., 122°46' W. (Lanphere and others, 1968, table 7, sample 32).
41. Quartz monzonite; 41°48'30'' N., 122°45'30'' W. (Lanphere and others, 1968, table 7).
42. Gabbro; 41°56'45'' N., 122°45'45'' W. (Lanphere and others, 1968, table 7).
43. Gabbro; 41°58'45'' N., 122°46'30'' W. (Lanphere and others, 1968, table 7).
44. Quartz diorite; 41°56'45'' N., 122°45'15'' W. (Lanphere and others, 1968, table 7, sample 31).
45. Quartz diorite; approximately 42°1'30'' N., 122°47' W.; new analysis.
46. Granodiorite; 42°10'30'' N., 122°44'30'' W.; new analysis.
47. Granodiorite; 41°58'15'' N., 122°46'15'' W. (Lanphere and others, 1968, table 7, sample 30).
48. Quartz diorite; 42°20' N., 122°58'30'' W.; new analysis.
49. Granodiorite; 42°26'30'' N., 122°59'45'' W.; new analysis.
50. Quartz diorite; 42°7'45'' N., 122°59'45'' W.; new analysis.
51. Gabbro; 42°9'30'' N., 123°19'30'' W.; new analysis.
52. Quartz diorite; 42°8'30'' N., 123°21'30'' W.; new analysis.
53. Quartz monzonite; 42°28'45'' N., 123°21' W.; new analysis.
54. Trondhjemite; 42°41' N., 123°2'30'' W.; new analysis.
55. Trondhjemite; 42°39'30'' N., 123°3' W.; new analysis.
56. Quartz gabbro; 42°33'15'' N., 123°41' W.; new analysis.
57. Quartz gabbro; 42°22'30'' N., 123°48'30'' W.; new analysis.
58. Quartz diorite; 42°33' N., 123°42' W.; new analysis.

Klamath Mountains. Most of them occur in the Trinity Mountains plutonic belt (fig. 10; Lanphere and others, 1968), where they range in age from 127 to 140 m.y. (million years). Only one, the White Rock pluton, has been recognized in Oregon. Muscovite from this pluton yielded a potassium-argon age of 138 m.y.

The trondhjemites are essentially light-colored oligoclase-quartz diorites. Those whose plagioclase is andesine, Davis (1963) called calcic trondhjemite. Mica is the predominant mafic mineral. In the California plutons, biotite is the chief mica and is accompanied by some muscovite; however, muscovite is the predominant mica in the White Rock pluton. Hornblende is either absent or present in subordinate amounts.

The Mule Mountain stock in the southern Klamath Mountains is mostly trondhjemite (Kinkel and others, 1956, p. 43–48). It is extensively altered and silicified and is associated with albite granite that may have been formed by albitization of the trondhjemite (Albers, 1964, p. J34). The Mule Mountain trondhjemite has been interpreted to have formed in large part by metasomatism (Albers, 1964, p. J35).

On the modal quartz-plagioclase-potassium feldspar diagram (fig. 4) the trondhjemites plot in the upper part of the quartz diorite field near and on the quartz-plagioclase join.

GRANODIORITE

Rocks classified as granodiorite seem less abundant than quartz diorite, but this may be because of inadequate sampling and insufficient mapping of most of the Klamath plutons. In some of the larger plutons that have been more thoroughly studied, granodiorite is predominant. For example, the rock type of about two-thirds of the English Peak (Seyfert, 1965), the Russian Peak (Davis and others, 1965), and the Shasta Bally (Albers, 1964) plutons is granodiorite. The central part of these plutons is granodiorite; the outer parts are composed of quartz diorite or more-mafic rocks.

The granodiorites are typically medium-grained hypidiomorphic-granular rocks which are slightly porphyritic in places. Their color index is commonly about 10, but ranges from as little as 5 to as much as 30. The quartz content is greater than 10 percent and is as high as approximately 30 percent. The ratio of potassium feldspar to total feldspar is from about one-tenth to one-third.

Plagioclase, the most abundant light-colored constituent, is subhedral to euhedral, well twinned, and zoned. Most commonly it is fresh, although the internal parts of crystals may be somewhat saussuritized. The composition of individual crystals varies widely, but the average anorthite content is most commonly An_{20}–An_{40} (medium oligoclase to medium andesine).

Quartz is in anhedral interstitial grains, and almost all is strained. Anhedral potassium feldspar occurs interstitially also, and commonly it markedly embays and encloses plagioclase. Some of the granodiorite from the Castle Crags pluton is porphyritic, with subhedral to euhedral phenocrysts of potassium feldspar poikilitically enclosing corroded grains of plagioclase. The potassium feldspar most commonly appears as untwinned microperthitic bodies, but in some specimens it shows microcline twinning. Myrmekite is common on the boundaries between potassium feldspar and plagioclase.

The chief mafic minerals are green hornblende and biotite. Biotite is commonly more plentiful than hornblende, but in some specimens the two are of approximately equal abundance. Biotite is anhedral, and hornblende subhedral to euhedral. Biotite is partly replaced by chlorite in some specimens.

Clinopyroxene (augite) is a minor constituent of a few of the granodiorites. Almost invariably it is rimmed by hornblende. An unusually pyroxene-rich granodiorite occurs apparently as a small satellitic body in the southern part of the Ashland pluton. Specimens of this rock, which contain about 11 percent quartz, 10–13 percent potassium feldspar, and approximately 45 percent zoned plagioclase (An_{60}–An_{40}), contain as much as 12 percent pyroxene, including hypersthene and augite. In one specimen the pyroxene occurs as small phenocrysts. Hornblende and biotite are also present, the hornblende partly replacing pyroxene.

Other common accessory minerals are magnetite, sphene, and apatite. A few small grains of zircon are present.

QUARTZ MONZONITE AND ALASKITE

Rocks classified as quartz monzonite (adamellite) are apparently rare, but may be more common than the limited sampling indicates.

A sample from the central part of the Grants Pass pluton is a medium-grained hypidiomorphic-granular rock with a color index of 7. Its quartz content is 26 percent, potassium feldspar 25 percent, and plagioclase 42 percent. Plagioclase crystals are subhedral and well twinned and show oscillatory zoning. The central parts range from An_{25} to An_{29}, and the rims are sodic oligoclase (An_{15}). Some zones are saussuritized. Large anhedral plates of generally untwinned white potassium feldspar wrap around and poikilitically enclose the plagioclase. Quartz forms large anhedral grains. Biotite, partly altered to chlorite, is the principal mafic mineral, but small amounts of pale-green hornblende also are present. Metallic opaque minerals are minor.

A small alaskitic pluton cuts quartz diorite in the eastern part of the Vesa Bluffs pluton. This light-colored pinkish fine-grained hypidiomorphic-granular rock contains only about 3 percent dark minerals. Subhedral slightly zoned plagioclase (An_{34}) is surounded and embayed by anhedral quartz and potash feldspar. The potash feldspar all shows microcline twinning. Quartz amounts to about 33 percent of the rock, potassium feldspar 24 percent, and plagioclase 40 percent; white mica and less than 1 percent of pyrite constitute the balance. The mica is in the form of tiny flakes in plagioclase (sericite) and as a few larger interstitial flakes of muscovite.

The central part of the predominantly granodioritic English Peak pluton grades to quartz monzonite (Seyfert, 1965), which constitutes 8 percent of the exposed area of the batholith. Quartz ranges from 31 to 34 percent, potassium feldspar 20 to 24 percent, and plagioclase (An_{20}–An_{23}) 35 to 39 percent. Biotite (5–7 percent) is the principal mafic mineral and is partly chloritized. Hornblende amounts to less than 1 percent.

CHEMICAL DATA AND COMPOSITIONAL TRENDS

Fifty-eight chemical analyses of samples from plutons in the Klamath Mountains are given in table 1. In addition to analyses of "granitic rocks," some more-mafic rocks including diorite and gabbro, which are believed to be consanguineous, are also included. The sampling is unevenly distributed. Some plutons are represented by several analyses, while only a single analysis is available for others. The data are probably sufficient, however, to demonstrate the broad chemical features of the rocks and to illustrate the general trend of their variation.

In figure 5 the major oxides are plotted on standard silica-variation diagrams. For rocks containing 55 percent SiO_2 or more, the trends of the oxides are fairly definite and expectable: as SiO_2 increases, Al_2O_3, total Fe, MgO, and CaO decrease, while Na_2O and K_2O increase. The trondhjemitic rocks are, however, obvious exceptions to these general trends: Al_2O_3 is higher than average for the high-silica rocks, Na_2O is slightly higher, and K_2O is markedly below the average. Below 55 percent SiO_2 the points for Al_2O_3, total Fe, and MgO are so scattered that the trend for these oxides cannot be defined. Obviously, however, some of the specimens from the Ironside Mountain pluton contain greater-than-average K_2O compared with the other rocks in this silica range. The silica-variation diagrams, as applied to these rather heterogeneous data, are less informative than plots of ternary ratios between various components, which are considered in the succeeding discussion.

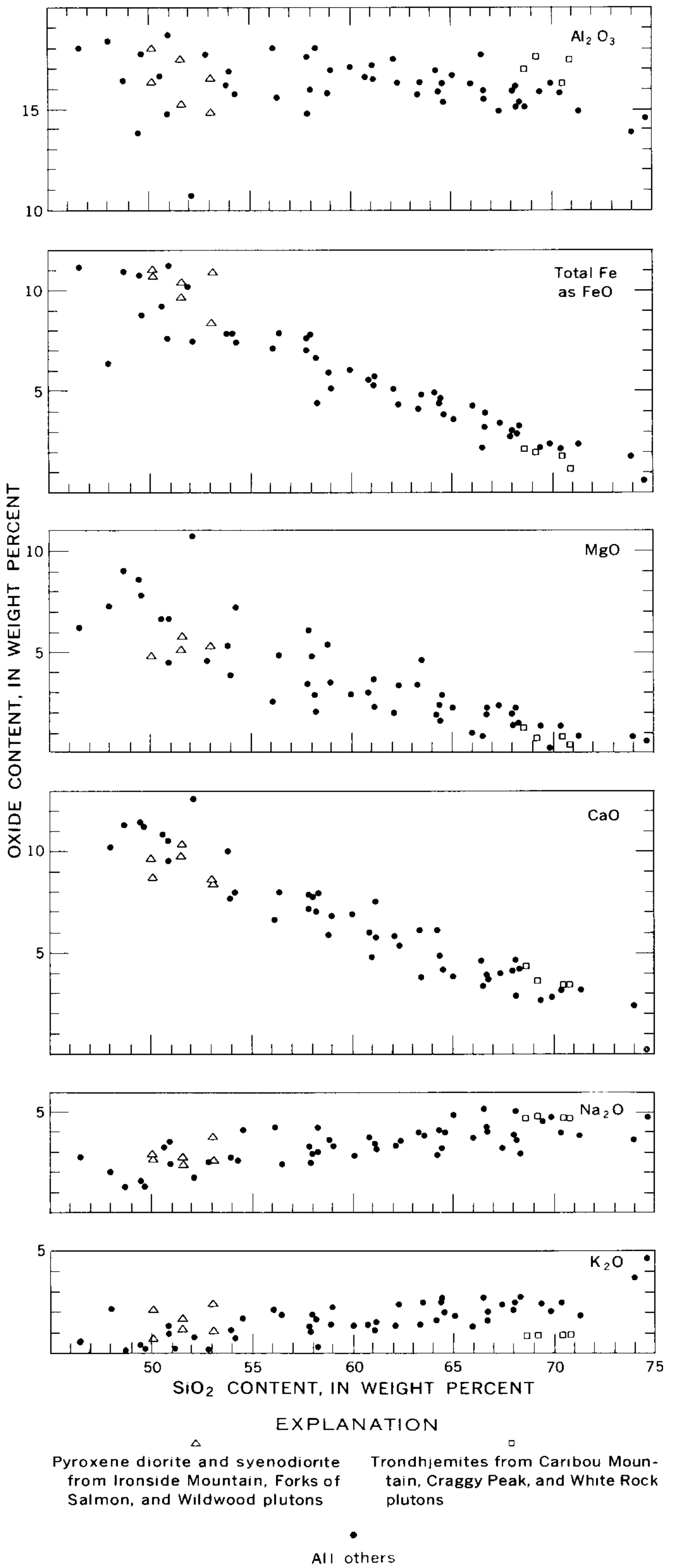

FIGURE 5.—Variation of common oxides in plutonic rocks of the Klamath Mountains plotted against SiO_2.

The ternary ratios of the normative minerals quartz-orthoclase-plagioclase, derived from the analyses (table 1), are plotted in figure 6. For comparison, norms of some of Nockolds' (1954) average rocks and two of Goldschmidt's (1916, p. 79; 1921, p. 20) trondhjemites are also plotted on the diagram. The granitic rocks (quartz>10 percent) have a fairly well defined trend and plot somewhat closer to average tonalite (quartz diorite) and the trondhjemites than to granodiorite. Only one rock plots near average adamellite (quartz monzonite). The four trondhjemites with their relatively low normative orthoclase are clearly separated from other rocks which have approximately equivalent normative quartz and plagioclase. Norms of analyzed specimens from the Ironside Mountain pluton and of one specimen from the Forks of Salmon pluton fall near the plagioclase-orthoclase join, two near average diorite and one near average mangerite.

In figure 7 both modal and normative quartz-orthoclase-plagioclase of chemically analyzed rocks are plotted. With a few exceptions, the modes and norms are rather widely separated, and in nearly every instance the normative plot is displaced toward the orthoclase corner. In other words, the analyses show more normative orthoclase than modal potassium feldspar.

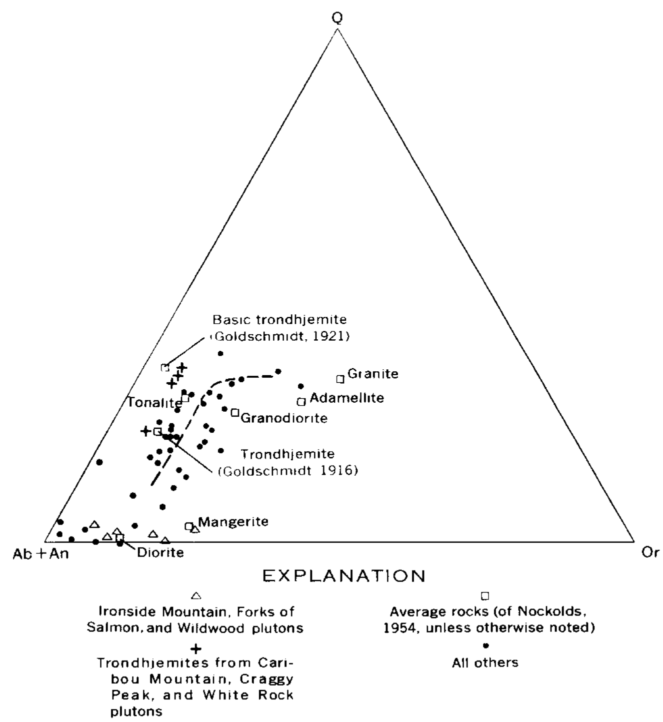

FIGURE 6.—Normative quartz-orthoclase-plagioclase (Ab+An) ratio for plutonic rocks of the Klamath Mountains.

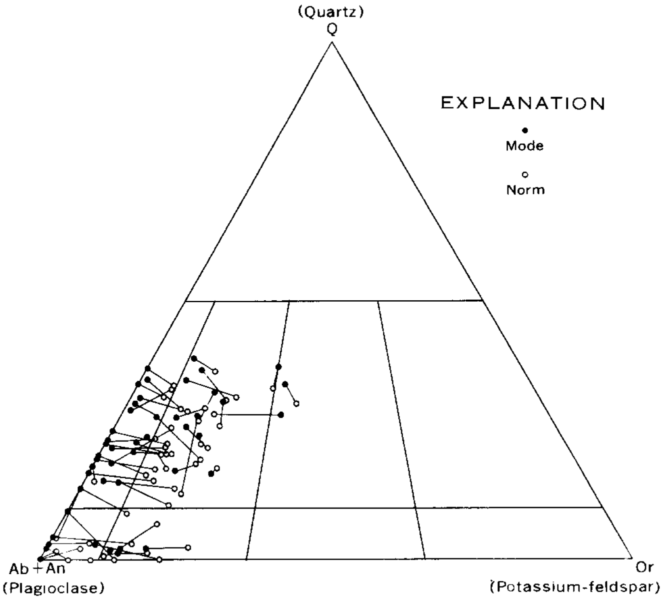

FIGURE 7.—Comparison of modal and normative quartz-orthoclase-plagioclase (Ab+An) ratios for plutonic rocks of the Klamath Mountains.

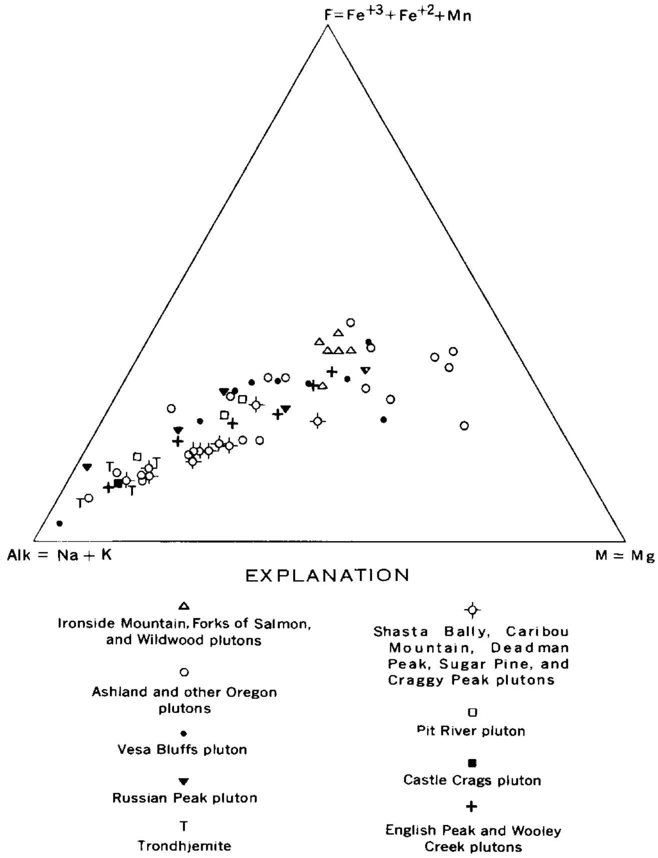

FIGURE 8.—Alk–F–M ratio (cation percent) for plutonic rocks of the Klamath Mountains.

Presumably this is because K_2O of biotite and, to a lesser extent, of plagioclase and hornblende is calculated as normative orthoclase, and the amount of albite in solid solution in modal potassium feldspar is insufficient to counterbalance this effect. A notable exception is the sample from the Grants Pass pluton, whose modal constituents plot in the quartz monzonite field but whose normative orthoclase is approximately 11.5 percent lower than modal potassium feldspar, which possibly contains albite in solid solution. The potassium feldspar, however, shows no perthitic intergrowths under the microscope. For about six rocks the plagioclase-potassium feldspar ratio is fairly constant between norm and mode, but modal quartz is greater than quartz in the norm. The difference is only a few percent for most, but for two it is more than 10 percent. The discrepancies probably result from inhomogeneities in the material selected for chemical and modal analyses, or inadequate sampling, or both.

Two other ternary ratios, Alk–F–M and sodium-potassium-calcium (figs. 8, 9), illustrate some features of the rock chemistry which are not so apparent in the normative quartz-orthoclase-plagioclase (Ab+An) diagram and are useful in making comparisons with rocks from other provinces. The Alk–F–M diagram shows a fairly well defined trend, and the data suggest that different plutons and groups of plutons may have slightly different chemical characteristics. Analyses for the Ironside Mountain and related plutons (Forks of Salmon and Wildwood) group closely together in the mafic part of the diagram, however, possibly because sampling has been insufficient to discover more alkaline members of the suite.

The generally sodic composition of the rocks and the very slight potassium enrichment along the trend from right to left are apparent in the sodium-potassium-calcium diagram (fig. 9). The trondhjemites are well below the general trend, toward the sodium corner, as if they were the terminal product of a subsidiary branch. Davis (1963, p. 346–347), Davis, Holdaway, Lipman, and Romey (1965, p. 962) and Lipman (1963, p. 1277–1279), on the basis of limited data, first called attention to the divergence of quartz dioritic rocks of the south-central Klamath Mountains from the calc-alkaline trend toward what they called a trondhjemitic trend. A similar observation was made by Larsen and Poldervaart (1961) for the Bald Rock batholith in the northwestern Sierra Nevada.

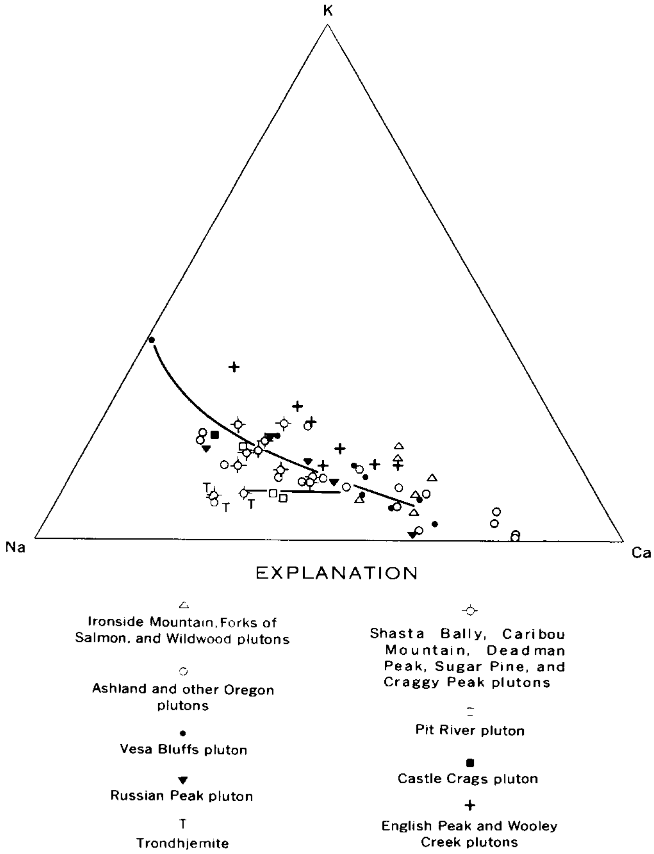

FIGURE 9.—Sodium-potassium-calcium ratio (cation percent) of plutonic rocks of the Klamath Mountains.

AGE

Stratigraphic evidence for the age of the Klamath Mountains plutons is sparse. The youngest rocks they intrude are of Late Jurassic (Kimmeridgian) age. The oldest strata, which lie depositionally on eroded granitic plutons, are of Early Cretaceous (Hauterivian) age in the southeastern part of the province and of Late Cretaceous (Cenomanian and Turonian) age in the northeastern part of the province. Potassium-argon mineral ages have been determined, however, for specimens from most of the plutons in the California and Oregon parts of the Klamath Mountains (Lanphere and others, 1968, 1969). In the southern Klamath Mountains, granitic plutons form three fairly well defined belts that are differentiated on the basis of age (fig. 10). The oldest granitic rocks occur in the eastern Paleozoic belt, where the Pit River stock has a minimum age of 246 m.y. (Permian). Grouped with this stock is the Castle Crags pluton, for which a discordant pattern of mineral ages, ranging from 133 to 224 m.y., was obtained. The next younger group of plutons includes the Ironside Mountain, Forks of Salmon, and Wildwood plutons. These occur in the southwestern part of the province and are collectively called the Ironside Mountain plutonic belt. They yield ages of 165 to 167 m.y. Between the eastern and Ironside Mountain belts and occupying the south-central part of the province is the Trinity Mountains plutonic belt, from which dates of from 127 to 140 m.y. were determined. In the central and northern part of the province (the northern plutonic area), no clear belt-like distribution is apparent. The mineral ages determined on specimens from the plutons range from 136 to 160 m.y. Thus, the ages determined from the Klamath Mountains plutons, excluding the Pit River and Castle Crags bodies, are Middle and Late Jurassic.

COMPARISON WITH PLUTONS OF THE WESTERN SIERRA NEVADA

Modal and chemical data are scanty for plutons exposed in the western foothills of the Sierra Nevada. Most of the data are for the Merrimac (Hietanen, 1951) and Bald Rock (Compton, 1955; Larsen and Poldervaart, 1961) plutons at the north end of the western Sierra belt. Data for the small Rocky Hill stock in the southern part of the western Sierra belt are also available from a study by Putnam and Alfors (1965). A few analyses were obtained from a report by Turner (1894), and unpublished data were supplied by L. D. Clark (written commun., 1970).

The available modal data are summarized in a ternary diagram (fig. 11) for quartz-plagioclase-potassium-feldspar. The data fall predominantly in the quartz diorite and granodiorite fields. The trondhjemitic character of plutons in the northwestern Sierra Nevada was observed (Hietanen, 1951; Compton, 1955; Larsen and Poldervaart, 1961) before trondhjemites were recognized in the Klamath Mountains.

Chemical data for western Sierra plutons are somewhat more abundant than modal data. A normative quartz-orthoclase-plagioclase (Ab+An) plot (fig. 12) of western Sierra rocks occupies a field essentially like that for plutons of the Klamath Mountains (fig. 6), and the average trend is also similar. Furthermore, the fields on Alk–F–M and sodium-potassium-calcium plots (figs. 13, 14) are essentially alike for the western Sierra and Klamath Mountains.

The ages of plutons in the western Sierra Nevada correspond in general to dates obtained from samples of Klamath Mountains plutons. Plutons in the northern part of the western Sierra Nevada, west of the Melones fault and Mother Lode belt, range from 126 to 146 m.y. (Curtis and others, 1958; Evernden and Kistler, 1970).

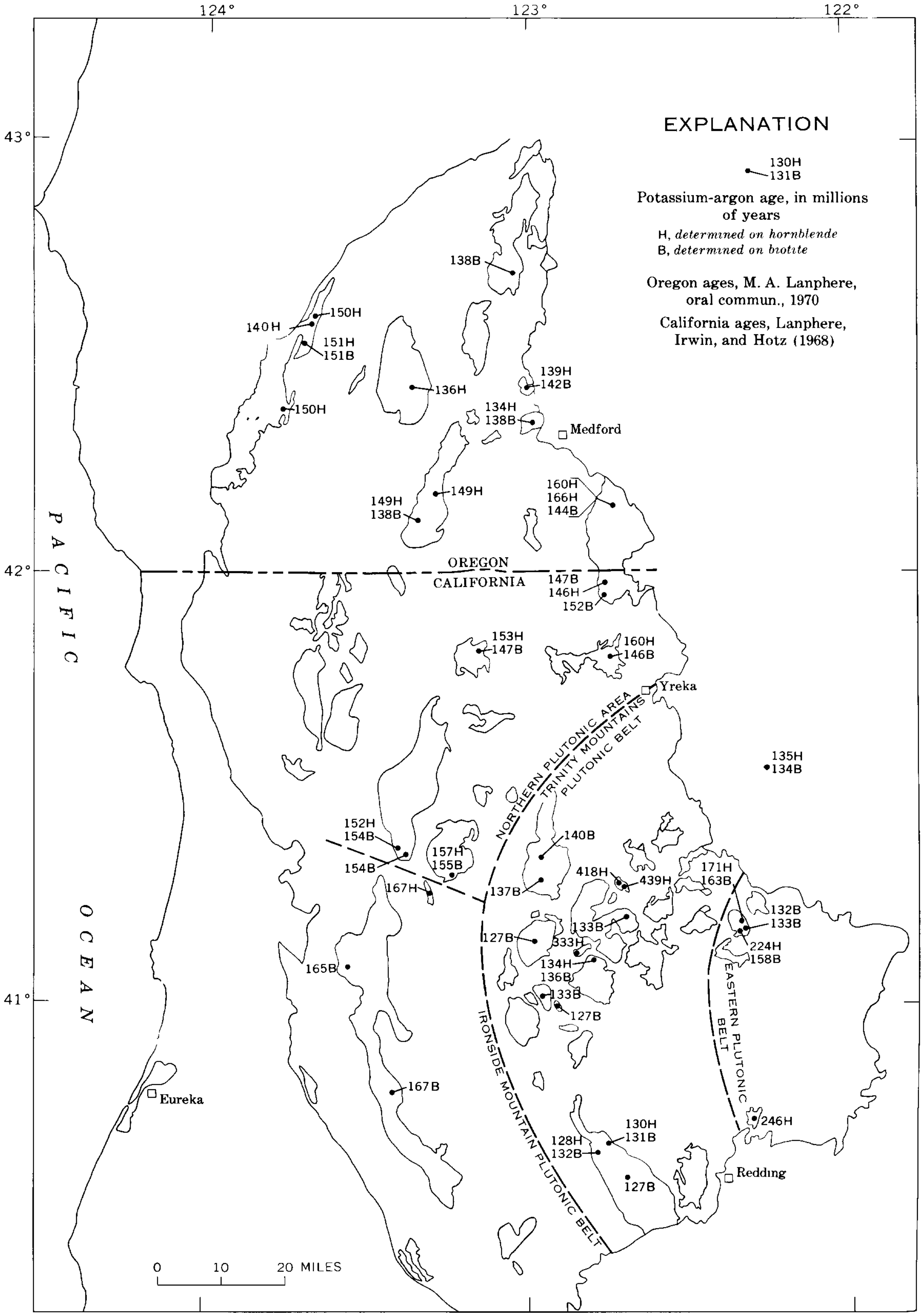

Figure 10.—Distribution of dated plutons in the Klamath Mountains.

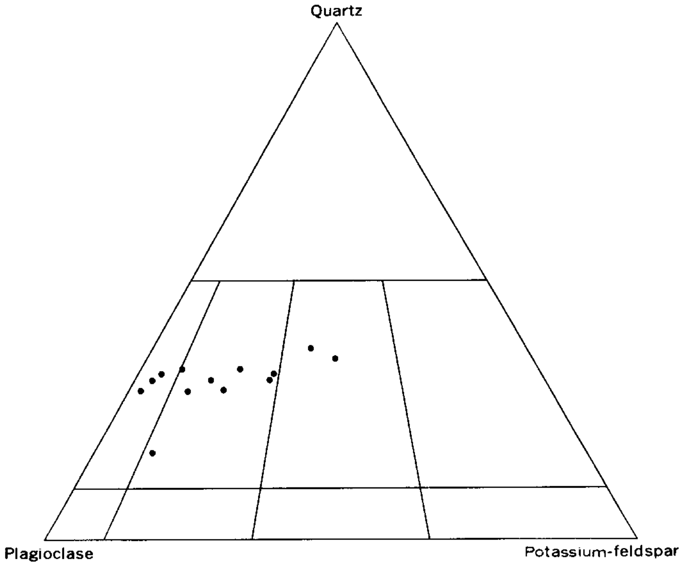

FIGURE 11.—Modal quartz-plagioclase-potassium-feldspar ratio for plutonic rocks of the western Sierra Nevada.

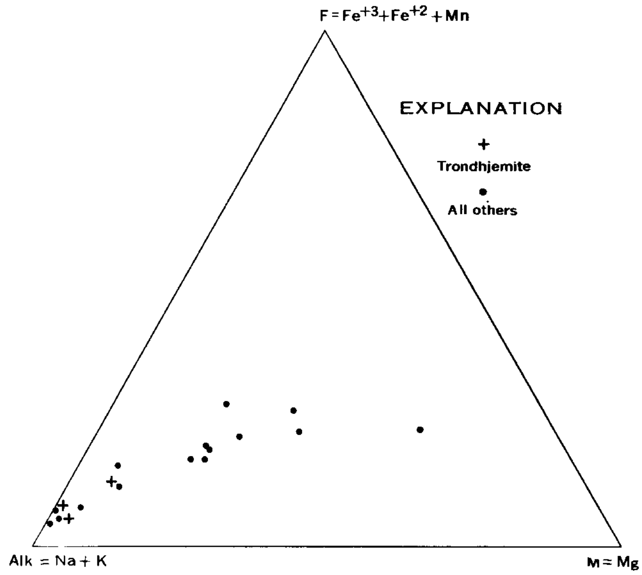

FIGURE 13.—Alk–F–M ratio (cation percent) for plutonic rocks of the western Sierra Nevada.

COMPARISON WITH PLUTONS OF THE CENTRAL SIERRA NEVADA

Previously published modal and chemical data for the east-central Sierra Nevada plutons are summarized in figures 15–18. The contrast in modal and chemical composition between the Klamath Mountains and east-central Sierra Nevada plutons is obvious. In general, the rocks of the east-central Sierra Nevada are more potassic, and granodiorite and quartz monzonite are predominant (fig. 15). The averaged trend line of normative quartz-orthoclase-plagioclase (fig. 16) for the east-central Sierra is straight and bisects the diagram from the direction of the plagioclase corner toward the center, and thus the ratio between quartz and orthoclase is essentially constant 1:1. This trend contrasts sharply with the trend for the Klamath Mountains plutons, which parallels the quartz-plagioclase join to about 30 percent quartz and then bends sharply toward the center (fig. 6). The well-defined field of the east-central Sierran rocks also encloses the plotted positions of Nockolds' (1954) average granodiorite, adamellite, and granite, whereas the field of the Klamath Moun-

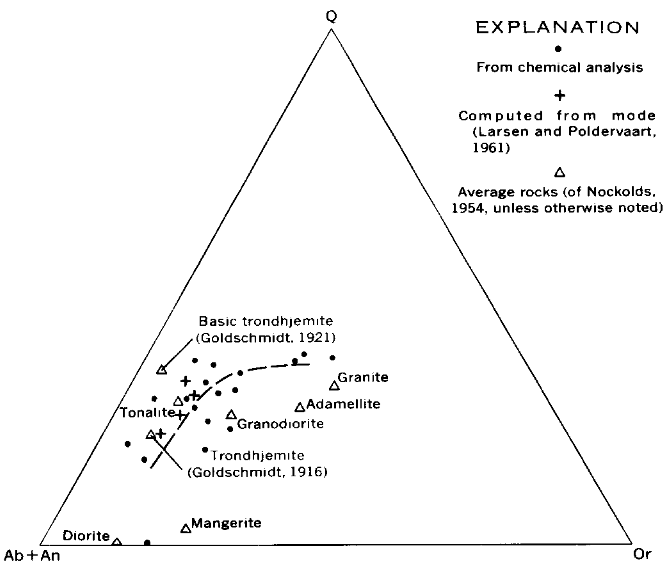

FIGURE 12.—Normative quartz-orthoclase-plagioclase (Ab+An) ratio for plutonic rocks of the western Sierra Nevada.

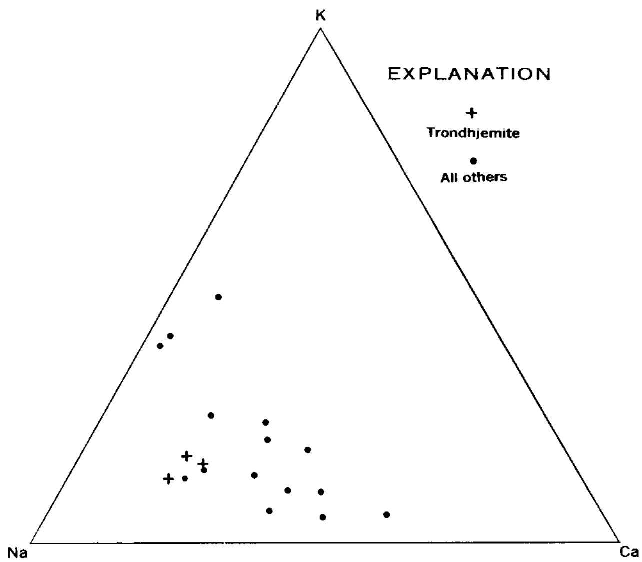

FIGURE 14.—Sodium-potassium-calcium ratio (cation percent) for plutonic rocks of the western Sierra Nevada.

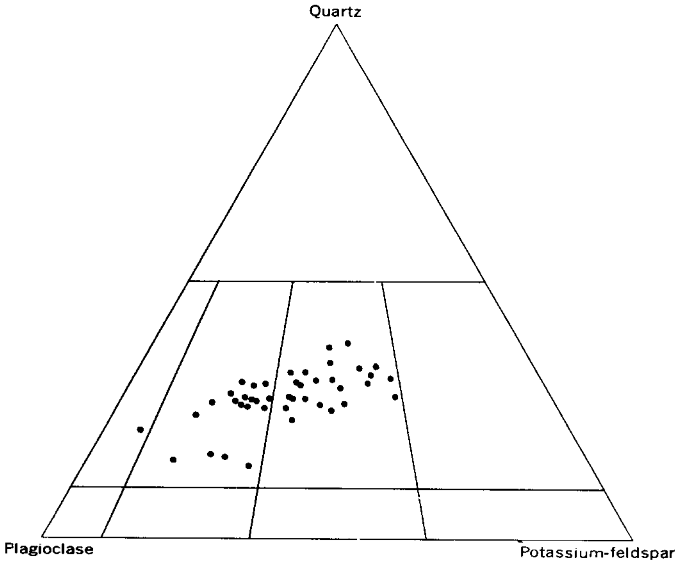

FIGURE 15.—Modal quartz-plagioclase-potassium feldspar ratio for plutonic rocks of the east-central Sierra Nevada (Bateman and others, 1963, fig. 15, p. D30).

tains plutons is more diffuse and enclose average tonalite and trondhjemite and just barely encloses average granodiorite. The difference in composition of plutonic rocks from the two provinces is also clearly illustrated by comparing (figs. 9, 18) plots of the ratios sodium-potassium-calcium which show the more potassic character of the east-central Sierran rocks.

Bateman and Dodge (1970) recently summarized the chemical constitution of the central Sierra Nevada batholith from the White Mountains east of the main

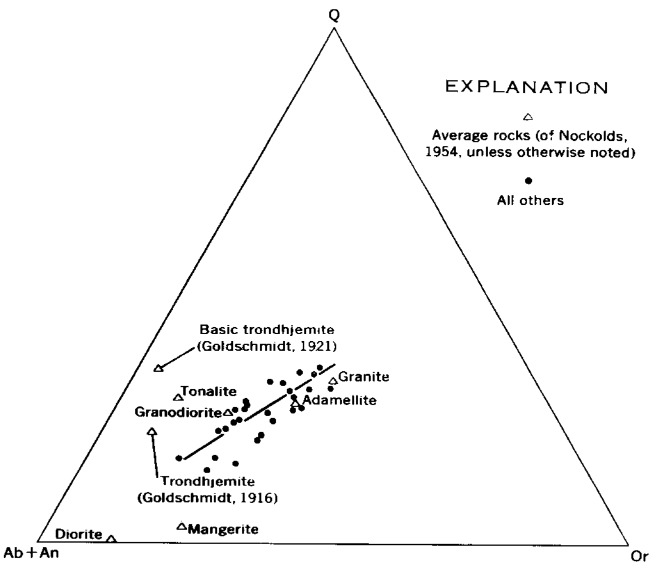

FIGURE 16.—Normative quartz-orthoclase-plagioclase (Ab+An) ratio for plutonic rocks of the east-central Sierra Nevada (Bateman and others, 1963, fig. 14, p. D30).

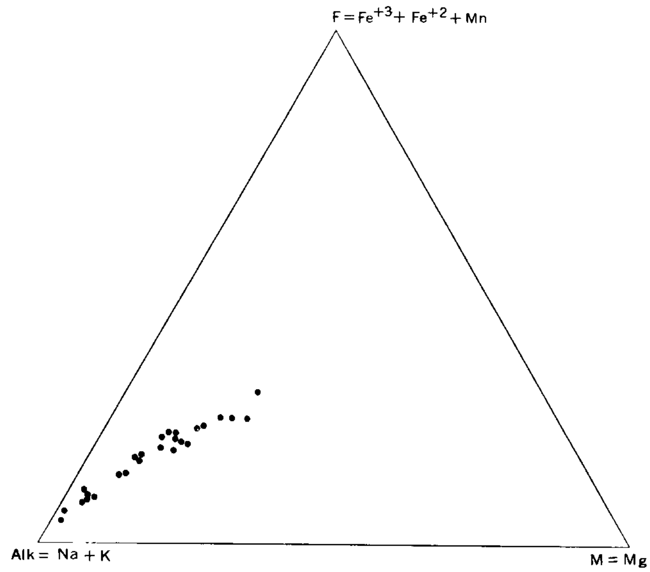

FIGURE 17.—Alk–F–M ratio (cation percent) for plutonic rocks of the east-central Sierra Nevada (computed from Bateman and others, 1963, table 3, p. D29).

Sierra Nevada to the western foothills. They tentatively assigned the plutons to eight comagmatic sequences which were emplaced during five intrusive episodes established by Evernden and Kistler (1970) and which range in age from 210 to 79 m.y. ago—Late Triassic to early Late Cretaceous. The composition of the plutonic rocks changes systematically across the Sierra Nevada batholith (Bateman and Dodge, 1970): from east to west K_2O clearly decreases, Fe_2O_3 and TiO_2 also decrease, and FeO, MgO, and CaO increase. The plutons

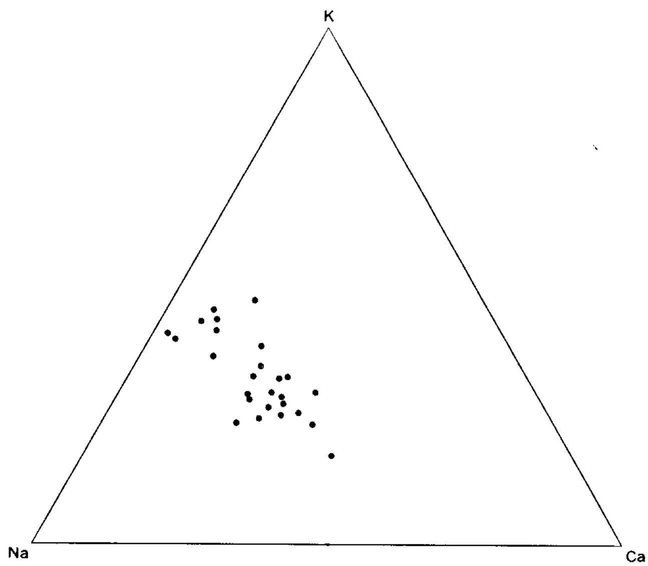

FIGURE 18.—Sodium-potassium-calcium ratio (cation percent) for plutonic rocks of the east-central Sierra Nevada (computed from Bateman and others, 1963, table 3, p. D-29).

east of the western foothills are obviously more potassic than Klamath Mountains plutonic rocks (fig. 19). The limited data from Klamath Mountains plutons do not show any east-west compositional trends comparable with those of the Sierra Nevada. The plot of the K_2O/SiO_2 ratios for the Klamath Mountains plutons (fig. 19) suggests, however, that within the Klamath Mountains province there may be compositionally similar groups of plutons. Certainly, theIronside Mountain plutonic belt contrasts sharply with other plutonic belts in the Klamath Mountains.

CONCLUSIONS

Plutonic rocks of the Klamath Mountains and the northwestern Sierra Nevada have many features in common. In both provinces the plutons intrude country rocks dominated by mafic volcanic rocks and eugeosynclinal sedimentary rocks. Bodies of ultramafic rock are abundant in both terranes. The plutonic rocks of both provinces have similar compositions, and their ages are in general the same. The petrologic and age data add support to the concept that the Klamath Mountains province is a northwestern continuation of the northwestern Sierra Nevada (Irwin, 1966, p. 28; Davis, 1969). Equivalents of the more potassic central and eastern Sierra plutons are lacking, however, and no Klamath Mountains plutons are as young as the Late Cretaceous plutons of the east-central Sierra Nevada. The few Klamath Mountains plutons that have been studied in detail show compositional variations which

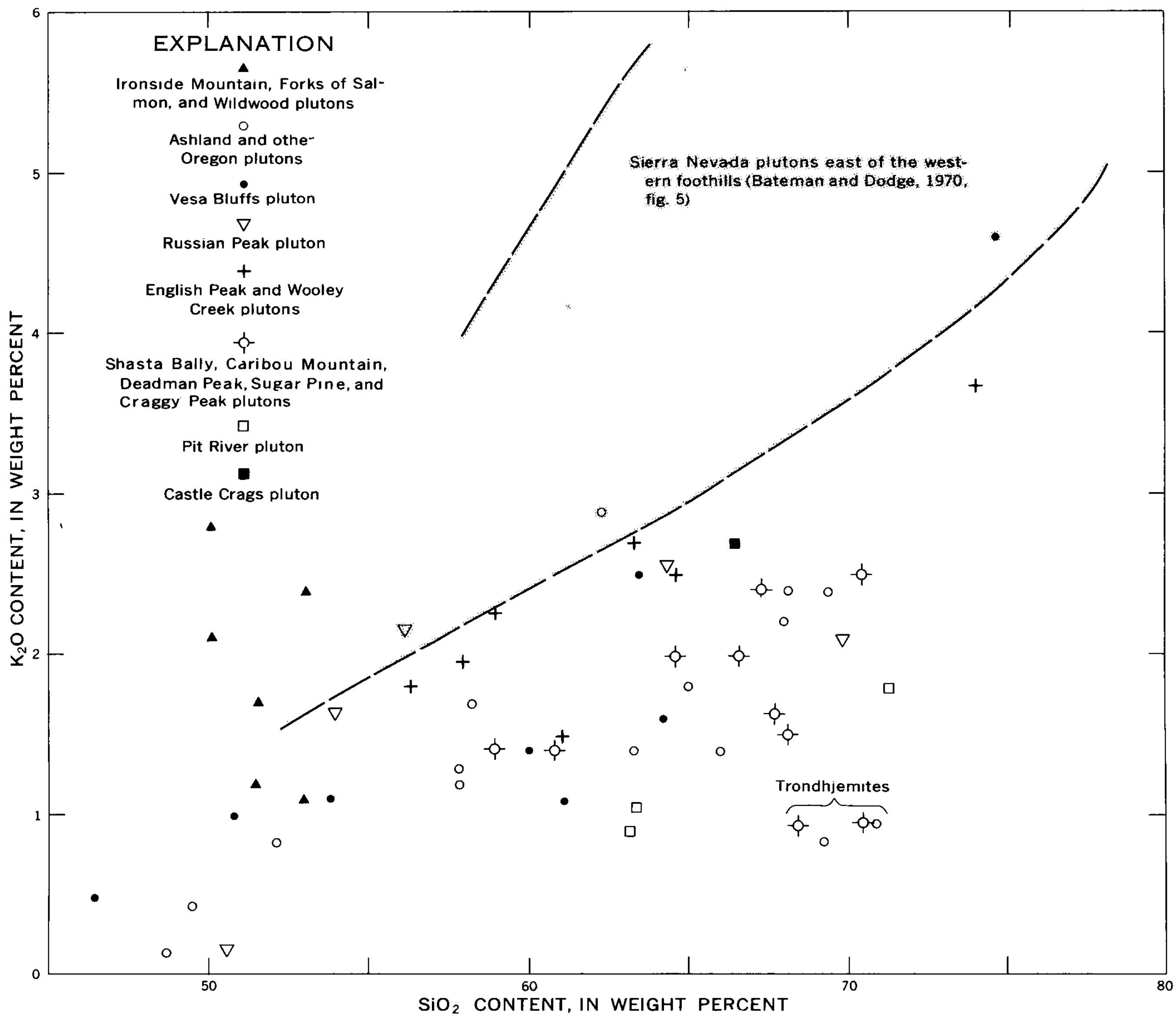

FIGURE 19.—Variation of K_2O/SiO_2 (weight percent) for plutonic rocks of the Klamath Mountains.

have been attributed to magmatic differentiation, multiple intrusion, assimilation of country rocks, or a combination of these (Davis and others, 1965, p. 962). A trend toward rocks of trondhjemitic composition is typical of the variation in several plutons; however, some have an almost normal calc-alkaline variation from diorite or gabbro to quartz monzonite.

Klamath Mountains plutons are relatively small, widely scattered bodies which vary considerably in texture and composition. Limited isotopic data suggest, however, that they can be assigned to three or possibly four groups according to age (Lanphere and others, 1968; 1969). Most of the plutonism occurred during the Middle and Late Jurassic Nevadan orogeny, during which there was also widespread regional metamorphism. Two small plutons in the eastern part of the province are pre-Nevadan and may be late Paleozoic. An older metamorphic event (Devonian) for which no contemporaneous plutonism has been recognized is recorded by rocks of the central metamorphic belt.

Moore (1959) called attention to fundamental differences in the composition of granitic rocks in the western United States on the basis of their geographic distribution and proposed the concept of the "quartz diorite boundary line." Granitic rocks west of the line are dominantly quartz diorite, and those to the east are dominantly quartz monzonite and granodiorite. The Klamath Mountains province and the western Sierra Nevada are west of the quartz diorite line, and their plutons have quartz diorite affinities.

Differences in composition east and west of the quartz diorite line have been attributed to fundamental compositional differences in the crust existing before emplacement of the granitic rocks: rocks east of the line were generated in a thick sialic layer with an initially higher K_2O content, whereas rocks west of the line originated in the sima or a thinner sialic layer with abundant geosynclinal sediments and volcanic rocks (Moore, 1959). It has also been suggested that age of emplacement may have been the factor controlling the difference in composition between the plutons of the Klamath Mountains and the central Sierra Nevada (Davis, 1963, p. 347; Davis and others, 1965, p. 963). As more data become available, however, it appears that composition is more dependent on position than on time of intrusion (Bateman and Dodge, 1970; Evernden and Kistler, 1970; Ross, 1969).

Bateman and Eaton (1967) postulated that granitic magmas of the Sierra Nevada were formed by anatexis in axial parts of a complex synclinorium on the margins of the continent. Westward decrease of K_2O in the plutonic rocks reflect progressive changes in composition of the geosynclinal rocks from epiclastic and carbonate sediments in the east to mafic volcanic and volcanic-derived sediments in the west. An alternate explanation for the observed change in K_2O content of the plutonic rocks from west to east is offered by recently published hypotheses correlating increase of K_2O in volcanic rocks toward the continents with increased depths of magma generation along or above landward-dipping subduction zones at continental margins (Dickinson, 1968; Dickinson and Hatherton, 1967; Hatherton and Dickinson, 1969). Applied to the California plutonic belt, these hypotheses would suggest that plutonic rocks of the Klamath Mountains and western Sierra crystallized from magmas generated at shallower depths along an eastward-dipping subduction zone than magmas which formed the central and eastern Sierra Nevada plutons.

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U. S. GOVERNMENT PRINTING OFFICE : 1971 O - 424- 041